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RESEARCH MEMORANDUM

FURTHER INVESTIGATION OF NACA 4-(5)(08) -03 TWO-BLADE

PROPELLER AT HIGH FORWARD SPEEDS

By

Melvin M. Carmel and Harold L. Robinson

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Langley Field, Va.

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RESEARCH MEMORANDUM

FURTHER INVESTIGATION OF NACA 4-(5)(08)-03 TWO-BLADE
PROPELLER AT HIGH FORWARD SPEEDS

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SUMMARY

Tests of an NACA 4-(5)(08)-03 two-blade propeller have been made in the Langley 8-foot high-speed tunnel for blade angles of 45° and 60° extending the Mach number range from that of previous tests of this propeller up to a forward Mach number of 0.913.

When the forward speed was increased from a low value to a forward Mach number of 0.90, the loss in peak efficiency for a $80.75R = 60^\circ$ was found to be not more than 47 percent. It was found that for propellers operating at supercritical speeds, the blade angle must be greater than for low-speed operations at a given advance ratio, and the power coefficient for peak-efficiency operation will be higher than that estimated from low-speed data. For operation at peak efficiency, the propeller tips experience compressibility effects first and these effects move inboard as the section speeds increase. When the tip section speeds increase further to speeds corresponding to the Mach number where the lift coefficient for two-dimensional data begins increasing (beyond critical speed), these sections assume load which had previously been lost due to compressibility effects. The efficiency of this propeller is higher than the jet-propulsive efficiency of a typical present-day jet below a Mach number of 0.82 with the jet operating at maximum continuous rated power.

INTRODUCTION

High-speed tests of propellers have already been performed up to forward speeds giving Mach numbers of the order of 0.725. With recent advances in the development of power plants, flight speeds considerably beyond Mach numbers of 0.725 are indicated. As a result, a high-speed propeller program has been initiated to evaluate the performance of propellers in the speed range above Mach numbers of 0.725. This was made possible by redesign of the Langley 8-foot high-speed tunnel and the use of a dynamometer with more power than

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the one used for previous tests. These studies are intended to investigate in detail the phenomena occurring in this high-speed range, to define propeller performance in this range, and to afford a comparison between propeller and jet efficiencies. The first phase of this program includes tests of the NACA 4-(5)(08)-03 propeller to a forward speed range up to Mach numbers of 0.9 with two blades and through a wide range of power coefficients.

During the early phases of these tests, mechanical difficulties necessitated removal of the dynamometer for repairs, thus delaying the program. Results of the two-blade tests of the NACA 4-(5)(08)-03 propeller at blade angles of 45° and 60° , as well as thrust wake surveys, were partially completed before the dynamometer difficulties set in.

SYMBOLS

$\beta_{0.75R}$	blade angle at 0.75 radius, degrees
r	radius to station on blade, measured from axis of rotation
r_s	radius to survey station in wake, measured from axis of rotation
R	propeller radius
X	fraction of propeller tip radius $\left(\frac{r}{R}\right)$
X_s	ratio of radius to survey stations in wake to radius of propeller $\left(\frac{r_s}{R}\right)$
V	velocity of advance, feet per second
n	propeller rotational speed, rps
D	propeller diameter, feet
J	advance ratio (V/nD)
M	Mach number of advance
M_x	Mach number at any blade station
M_t	helical tip Mach number $\left(M_t = M \sqrt{1 + \left(\frac{\pi}{J}\right)^2}\right)$

P	power
C_P	power coefficient $\left(\frac{P}{\rho n^3 D^5}\right)$
T	thrust
C_T	thrust coefficient $\left(\frac{T}{\rho n^2 D^4}\right)$
η	efficiency of propeller
η_p	jet-propulsive efficiency

APPARATUS AND METHODS

The tests were conducted in the Langley 8-foot high-speed tunnel. A sketch (fig. 1) shows the test setup and dynamometer details. The motors of the dynamometer were suspended by means of flex plates. Thrust and torque pressures were obtained by means of servovalves which built up pressure equal to that necessary to keep the thrust or torque arm in a null position. These pressures were then measured on a calibrated manometer board. By means of this type of measuring system, propeller efficiencies rather than propulsive efficiencies were obtained. The data for previous tests of this propeller, for which the Mach number range was not as great, were for propulsive efficiencies (reference 1). A rake (not shown in fig. 1) was used to obtain thrust wake-survey measurements. This rake was fastened rigidly to the wall and dynamometer barrel 70° from the vertical in order to be outside the influence of the strut supporting the front unit. The ends of the rake tubes were 18 inches behind the plane of the propeller.

The NACA 4-(5)(08)-03 propeller blades used for these tests were the same as those used in the tests of reference 1. Blade-form curves are given in figure 2. It may be seen from this figure that the spinner for the present tests is smaller than that used for the previous tests, the present spinner surface being at the $x = 0.271$ station and the previous spinner surface being at the $x = 0.33$ station.

These tests were limited as previously noted and were conducted for only two blade angles, $\beta_{0.75R} = 45^\circ$ and 60° . For a blade angle of 45° , tests were conducted up to a Mach number of 0.65 and for a blade angle of 60° , up to a Mach number of 0.913. At Mach numbers of 0.85 and above, peak-efficiency operation for a blade angle of 60° was not attained because of lack of power. This lack of power was a result of

only using two of the four motors during these tests because of mechanical difficulties encountered with the dynamometer. Both units were in place for these tests but only the two motors in the rear unit were used.

REDUCTION OF DATA

The force test data have been reduced to the usual thrust and power coefficients and have been corrected because of tunnel-wall constraint to the equivalent free-stream velocity (reference 2).

The accuracy to which the data could be reproduced is indicated by the test points on figures 3 and 4, and at peak efficiency the average scatter was of the order of 2 percent although for an isolated case the scatter became as great as 5 percent. Pressure forces acting on the spinner were measured and found to give corrections of less than 1 percent and therefore were not incorporated with the test results.

The thrust-coefficient gradient curves were computed from measurements of static- and total-pressure changes in the wake of the propeller. An explanation of the method used is given in reference 3.

RESULTS AND DISCUSSION

The propeller characteristic curves are presented in figures 3 and 4. For each value of free-stream Mach number, the propeller-thrust coefficient, power coefficient, and efficiency are plotted against advance ratio. A plot of helical tip Mach number against advance ratio is also included for each of the figures.

Figures 3 and 4 also afford a comparison between efficiencies for the present data and the efficiencies for data from previous model tests (references 1 and 4). For both blade angles tested, the thrust- and power-coefficient curves for the previous data (not presented) are essentially the same as those for present data up to the stall for Mach numbers up to 0.60. Starting at a Mach number of 0.60, however, values of both thrust and power coefficient obtained in the previous tests are smaller than the corresponding values obtained in the present investigation for $\beta_{0.75R} = 60^\circ$, and the discrepancy is relatively greater for the power coefficient than for the thrust coefficient. It may be noted from figure 3 that for

$\beta_{0.75R} = 45^\circ$, the agreement between all three sets of data is within 1.5 percent for peak efficiency and this is within the combined experimental accuracy of the data. For $\beta_{0.75R} = 60^\circ$ (fig. 4), the present tests are in good agreement with previous model tests through a Mach number of 0.53. Beyond a Mach number of 0.53, differences in efficiency occur which become as great as 6 percent at a Mach number of 0.65. These differences in efficiency may be the result of the following factors: first, the present data are for propeller efficiencies, whereas the previous data were for propulsive efficiencies. In obtaining the propulsive efficiencies, the wing-fuselage combination for the test setup recovered a certain amount of the rotational slipstream losses, which at $\beta_{0.75R} = 60^\circ$ are large. Second, the velocity at the propeller plane for the previous data was higher than the test data indicated by a velocity ratio

True velocity of 1.025 at the tip to 1.075 at the shank ($x = 0.33$).
Free-stream velocity
By using these new high velocities, which effect an angle of attack decrease, calculations show that the propeller section efficiencies, particularly at the root sections at high Mach numbers for $\beta_{0.75R} = 60^\circ$, will be higher than they would have been had the section velocities been the same as free-stream velocity. Free-stream velocity occurred at most of the sections for the present propeller tests. Third, the present data are for a propeller with 8.8 percent of the thicker, more inefficient shank sections exposed than were exposed for the previous tests. Calculations show the sum of the above differences to be of the order of magnitude to account for the discrepancies existing between the two sets of data at high speeds. These differences did not occur at the low speeds because they are indicated to be caused by a critical combination of high speeds and high blade angles away from the design conditions. Two-dimensional data also show very little change of drag coefficient or lift coefficient until the lift coefficient becomes large at high Mach numbers.

Curves of envelope and peak efficiency plotted against tip Mach number are presented in figure 5 for both blade angles. For $\beta_{0.75R} = 45^\circ$, which is approximately the design blade angle of the propeller, the curves show a loss in peak efficiency of 20 percent between low speeds and a tip Mach number of 1.2. The maximum forward speed attained for this angle was a Mach number of 0.65. If the peak-efficiency curve is compared with that obtained for the previous model tests, the curves will be very close to each other up to a tip Mach number of 1.0 but beyond this Mach number differences will be shown that will become as large as 5 percent at a tip Mach number of 1.07. These differences may be partially explained in view of the fact that at the higher forward Mach numbers, the tip Mach number curve becomes much steeper when plotted against advance ratio, and small inaccuracies in establishing the advance ratio for peak efficiency will result in

large differences in tip Mach number. These differences will not occur in the test range of previous data for $\beta_{0.75R} = 60^\circ$. The $\beta_{0.75R} = 60^\circ$ curves for the present tests extend into a forward Mach number range never before explored in propeller investigations. The envelope-efficiency curve extends only to a tip Mach number of 1.12, but the forward Mach number extends to 0.85. The envelope-efficiency loss between low speeds and a forward Mach number of 0.80 is of the order of 35 to 40 percent, which when compared with data for $\beta_{0.75R} = 45^\circ$ shows that as more of the blade enters the high-speed range where compressibility effects are encountered, corresponding losses occur. Data could not be obtained for peak efficiency at a forward Mach number greater than 0.80 because of power limitations, but the curves show that at a Mach number of 0.85, the peak efficiency will be above 51.5 percent and at a Mach number of 0.90 it will be above 46.5 percent.

The thrust-coefficient curves of figure 6 show similar characteristics to those obtained for the tests presented in reference 5. For the blade angle of 60° , however, the forward Mach number range for the present tests is much higher. Power-coefficient curves (fig. 7) are included for all thrust-coefficient curves presented.

The curves show that for constant blade angle, the advance ratio for zero thrust increases slightly with Mach number up to a Mach number that can be considered the critical speed of the blade and then decreases rapidly with further speed increases. The curves also show a tendency for this advance-ratio value to level off at a Mach number of 0.90. This indicates that for high-speed propellers having most of their sections operating beyond their critical speeds, the angles of attack of the propeller blade sections must be greater than for one operating in the lower Mach number region in order to sustain high efficiencies. Therefore, the blade angle must be greater for a given set of operating conditions in this high-speed range. An examination of these curves also shows that at the higher Mach numbers the differences in advance ratio between the zero power and thrust coefficients are spread more widely apart than at the lower Mach numbers, indicating that for peak-efficiency operation, a higher power coefficient will be necessary at high speeds than for low speeds. Consequently, in selecting a propeller for high-speed operations, low-speed estimates of power coefficient will be necessarily low and this effect should be taken into account.

Thrust-gradient curves for the two angles tested are shown in figures 8 and 9. Values of advance ratio are also given with these curves so that corresponding force-test results can be obtained from figures 3 and 4.

Figure 10 shows a comparison of force-test and wake-survey thrust coefficients for an advance ratio of 2.2 when $\beta_{0.75R} = 45^\circ$

and for an advance ratio at peak efficiency when $\beta_{0.75R} = 60^\circ$. The results of tests presented in reference 6 show that the values will not necessarily agree in magnitude because of the use of only one survey rake. The comparison given in figure 10, however, is presented to show the good qualitative agreement between the trends obtained from force data and integrated pressure measurements in the slipstream.

The curves on figure 11 give an idea of the magnitude of the effects of compressibility on thrust distributions along the propeller for a blade angle of 45° for an advance ratio of 2.2 throughout the test Mach number range. These curves show that compressibility losses occur at the tip beginning with a free-stream Mach number of 0.53, and the losses become more serious as the Mach number increases due to more of the blade sections entering a speed range beyond their critical speeds. Similar analysis was presented in reference 7. At a free-stream Mach number of 0.65, it may be noted that the shank thrust distribution drops off in magnitude from that for the lower Mach numbers, and it is believed that this is due to almost all of the propeller being beyond its section critical speeds, whereas for the lower Mach numbers the shank sections are operating below their critical speeds. The section Mach numbers for these operating conditions are presented in figure 12 and are computed from the relation

$$M_x = M \sqrt{1 + \left(\frac{\pi x}{J}\right)^2}$$

This assumes that there are no induced effects and corresponds to the velocity W_0

where

$$W_0 = \sqrt{V^2 + (\pi D x)^2}$$

Figure 13 shows the effects of compressibility on thrust distributions along the propeller blade for $\beta_{0.75R} = 60^\circ$ for peak-efficiency operation throughout the test Mach number range. A curve showing the change in advance ratio for the same operating conditions (peak efficiency) with Mach number is also presented on this figure. Assuming each section to be operating at design lift coefficient, the critical Mach number is exceeded at the $x = 0.80$ station at a forward Mach number of 0.65, and for all blade stations for all Mach numbers tested above 0.65. (See fig. 14.) At any other section lift coefficients the critical speeds will be lower.

Up to and including a Mach number of 0.65, the thrust-distribution curves all have the same general shape and show no adverse effects of

compressibility. Even at a Mach number of 0.65 where the critical speeds are exceeded for part of the blade, compressibility effects are not severe enough to produce a loss in thrust, possibly because of three-dimensional relief at the blade tip. At a Mach number of 0.70, however, the section thrust shows a distinct decrease at sections outboard of $x = 0.45$, showing that the critical speeds of the sections around the tip have been well exceeded, while those around the shank are still carrying their normal load. This effect would probably have been less severe had the advance ratio for peak efficiency for this Mach number been the same as that for the lower Mach number range.

At Mach numbers greater than 0.70, the shank sections are getting further beyond their critical speeds as the forward speed increases and they lose thrust rapidly, but the tip sections begin assuming load again. An analysis of these data shows that the tip sections are in a Mach number range well beyond their critical speeds where the lift-coefficient curve for two-dimensional data begins to increase and consequently allows higher thrust loads to be carried by these sections. It is believed that the dip in these curves occurring just outboard of the $x = 0.40$ station is in the forward speed range where the lift coefficient for two-dimensional data has reached its lowest level (beyond critical Mach number). The Mach number at which this occurs for these curves is about 0.88 with a scatter on each side of about 0.02 in Mach number. This figure ($M = 0.88$) is in close accord with that of similar two-dimensional airfoil data shown in references 8 and 9. The losses in shank thrust would probably not have occurred at as low a Mach number or have been as severe had the design blade angle for this propeller been say 60° instead of about 45° .

Figures 11 and 13 also show the change in position of maximum section thrust along the propeller radius with forward Mach number. For $\beta_{0.75R} = 45^\circ$, as the Mach number increased into the range where compressibility effects occur, the maximum section thrust moved its position inboard. As previously stated for this blade angle, however, the forward Mach number range did not extend to a value where all of the sections of the blade were well above their critical speeds. For $\beta_{0.75R} = 60^\circ$, the inboard movement of the maximum section thrust coefficient in the speed range where compressibility effects occur was noted again, but with further speed increase the position then moved outboard along the radius to a position even further out than it was for low-speed operations.

A comparison between the peak efficiencies obtained for this propeller and the efficiencies that can be obtained from a typical present-day jet is presented in figure 15.

The equation for jet efficiency, which is the same as that derived from the propeller momentum theory, was taken from reference 10

where

$$\eta_p = \frac{1}{1 + \frac{1}{2} \frac{\Delta V}{V_0}}$$

V_0 free-stream velocity

ΔV incremental velocity effected by jet (from performance curves of typical jet engine)

The curves in figure 15 show that for the blade angles tested, the propeller efficiencies are greater than those for a typical present-day jet operating at maximum rated power up to a Mach number of 0.820. This condition for the jet is equivalent to the climb and high-speed conditions for an airplane. This type of comparison includes the thrust per unit area rather than the absolute value of thrust and thus may be used as comparison for any size jet or propeller.

CONCLUSIONS

Tests of an NACA 4-(5)(08)-03 two-blade propeller in the Langley 8-foot high-speed tunnel for blade angles of 45° and 60° through the Mach number range extending up to 0.913, and beyond speeds previously investigated with this propeller, indicate the following conclusions:

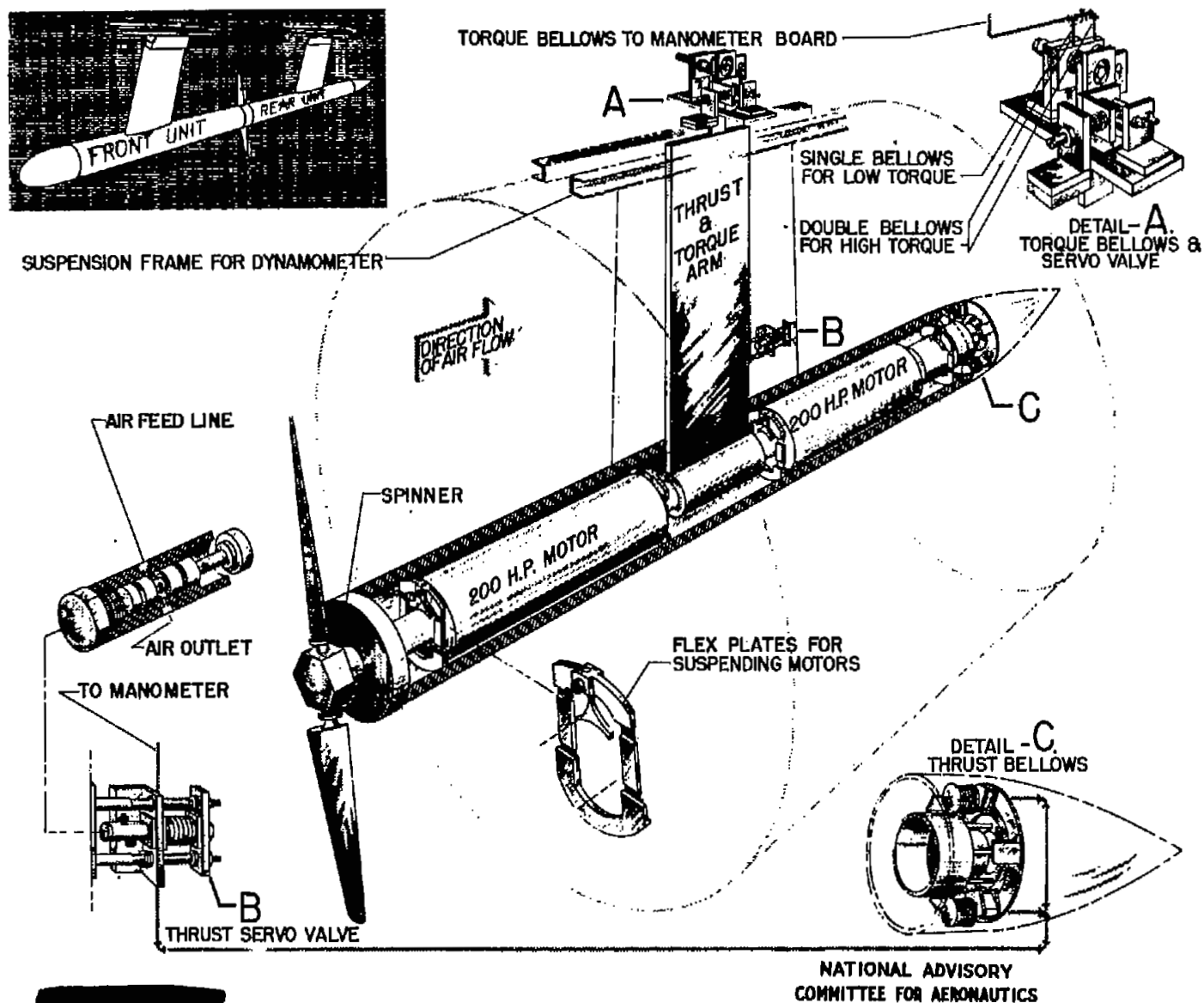
1. Propeller-efficiency losses not greater than 47 percent occurred for $\beta_{0.75R} = 60^\circ$ by increasing the forward Mach number from a low-speed value to 0.90.
2. For propellers operating at supercritical speeds, the blade angle must be greater than for low-speed operation at a given advance ratio, and the power coefficient for peak-efficiency operation will be higher than that estimated from low-speed data.
3. For peak-efficiency operation, the tips of propellers experience compressibility effects first and these effects move inboard as inboard section speeds increase to and beyond their critical speeds. When the tip section speeds increase further to speeds corresponding to the Mach number where the lift coefficient for two-dimensional data begins increasing (beyond their critical speed), these sections assume load which had previously been lost due to compressibility effects.

4. The efficiency of this propeller is higher than the jet-propulsive efficiency of a typical present-day jet below a Mach number of 0.82 with the jet operating at maximum continuous rated power.

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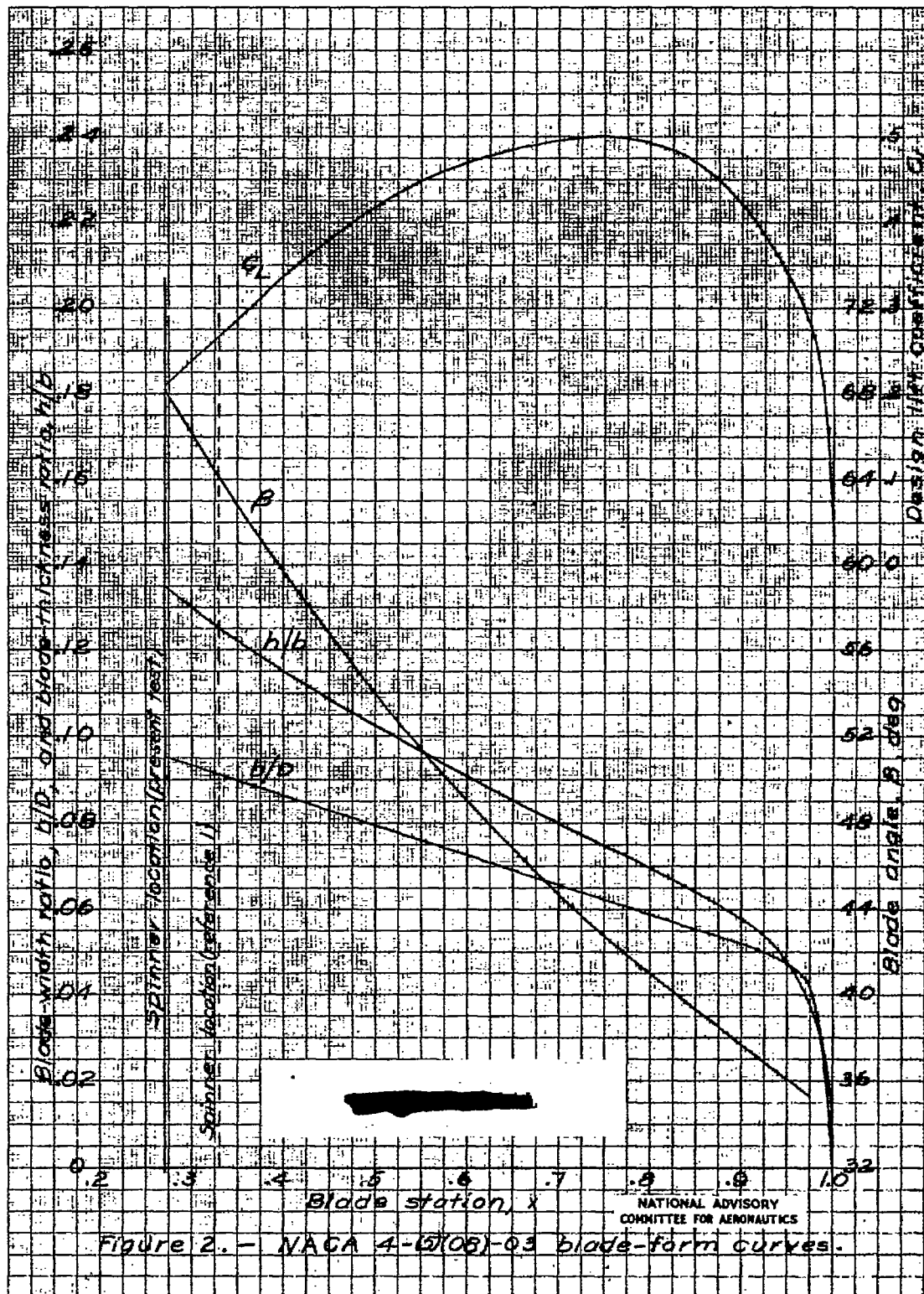


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Figure 1.- Test setup and dynamometer details.

Fig. 2

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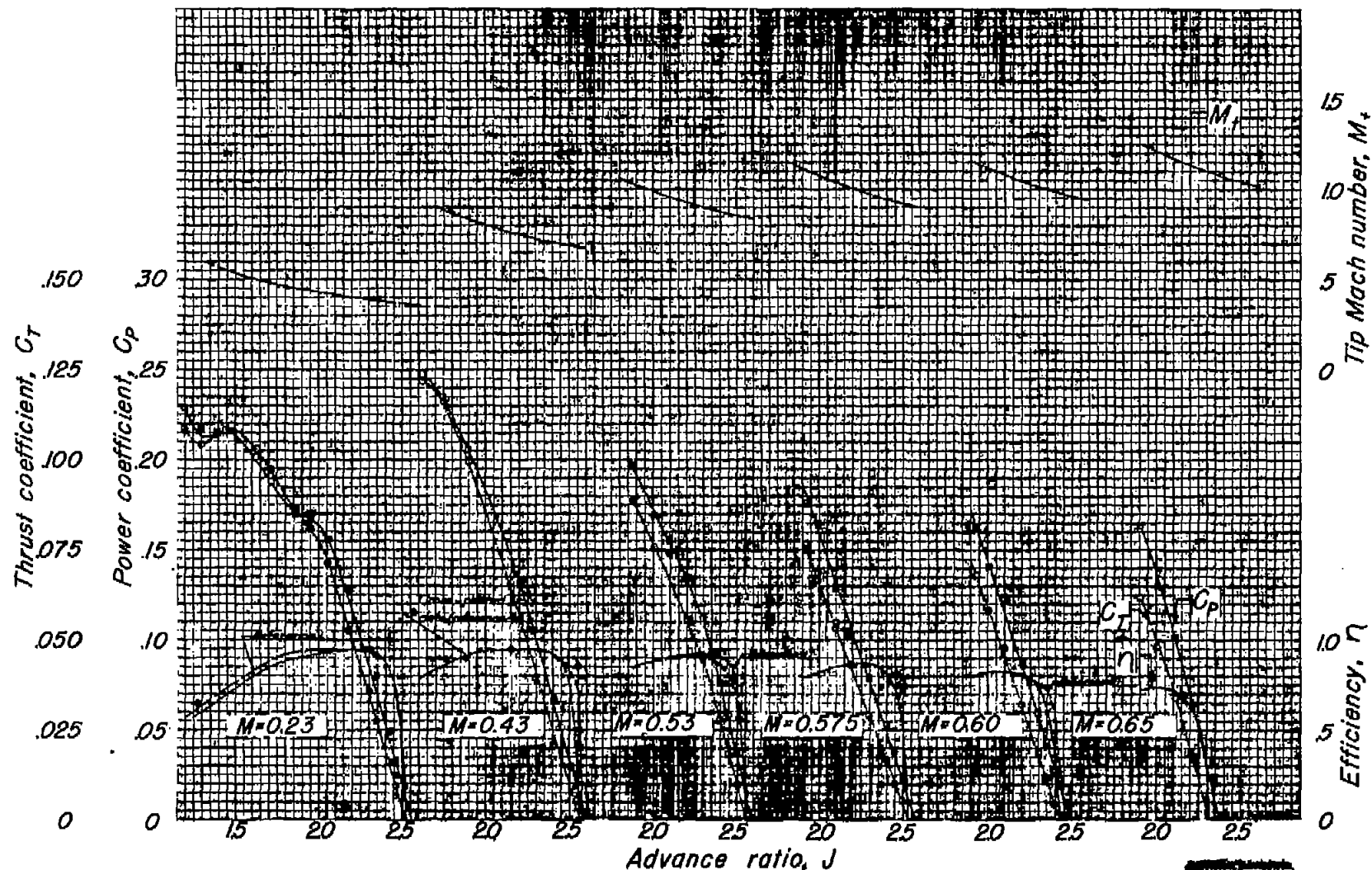


Figure 3.- Characteristics of NACA 4-(5)(08)-03 propeller. $\beta_{0.75R} = 45^\circ$

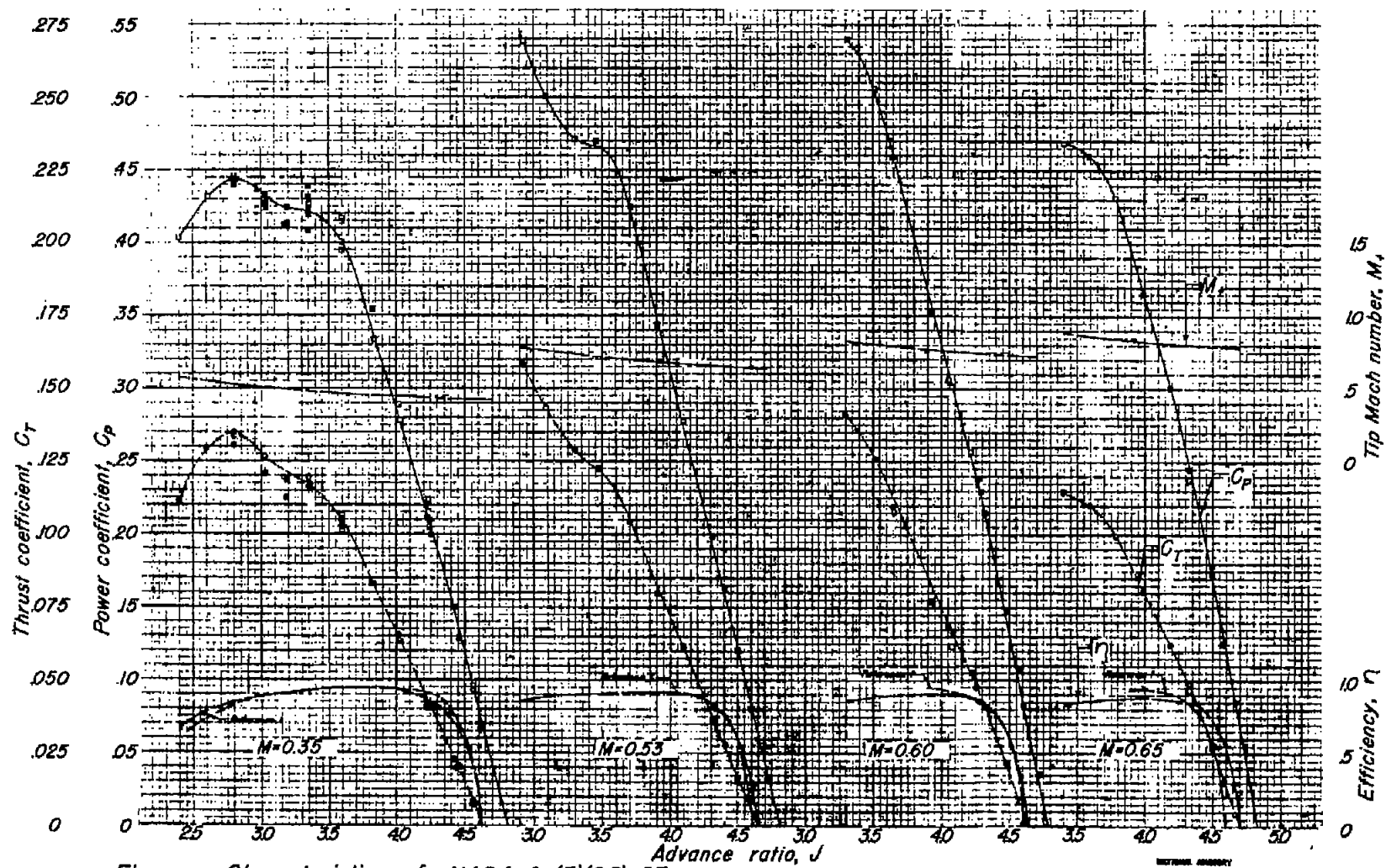


Figure 4.- Characteristics of NACA 4-(5)(08)-03 propeller. $\beta_{0.75R} = 60^\circ$

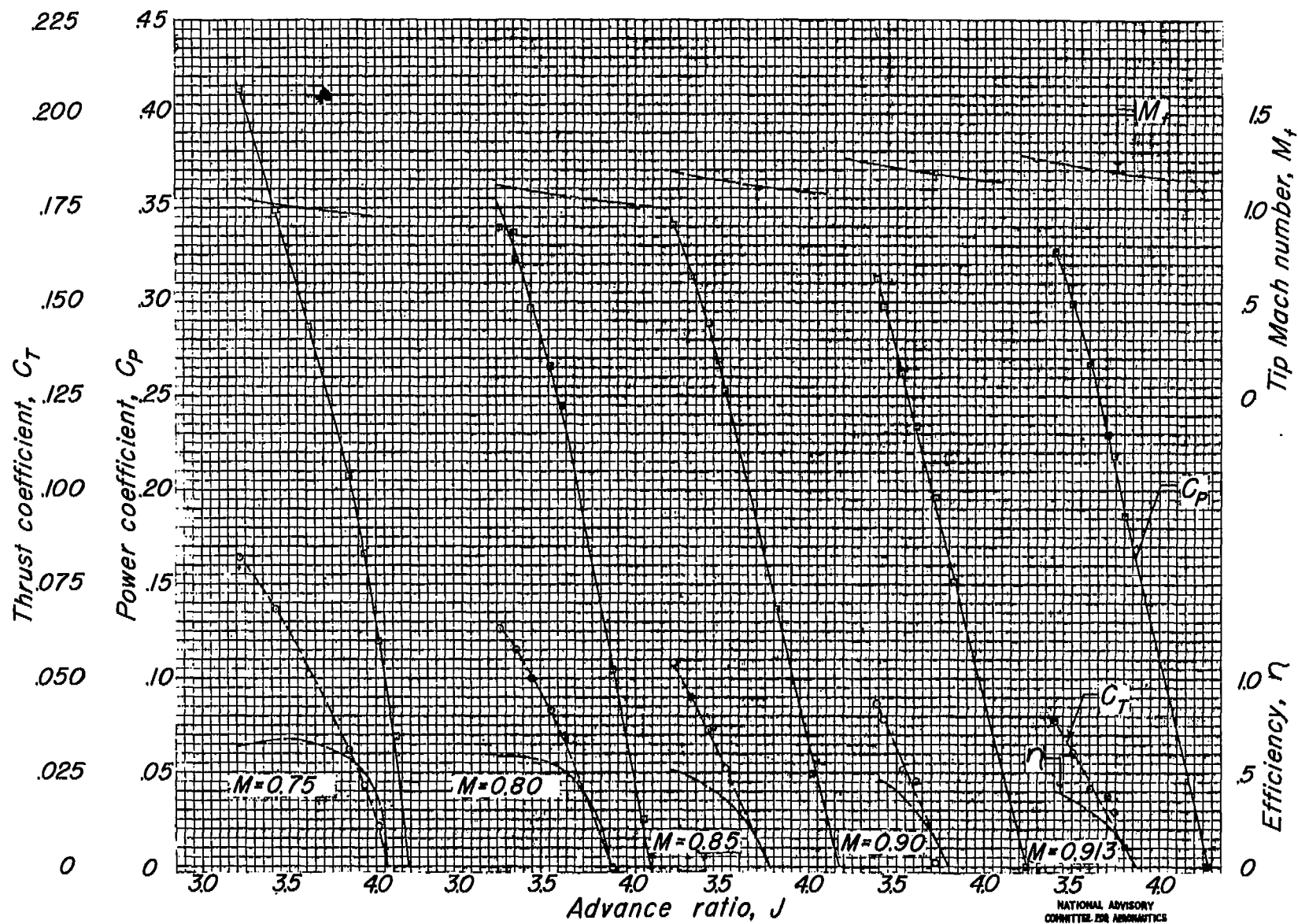


Figure 4- Concluded.

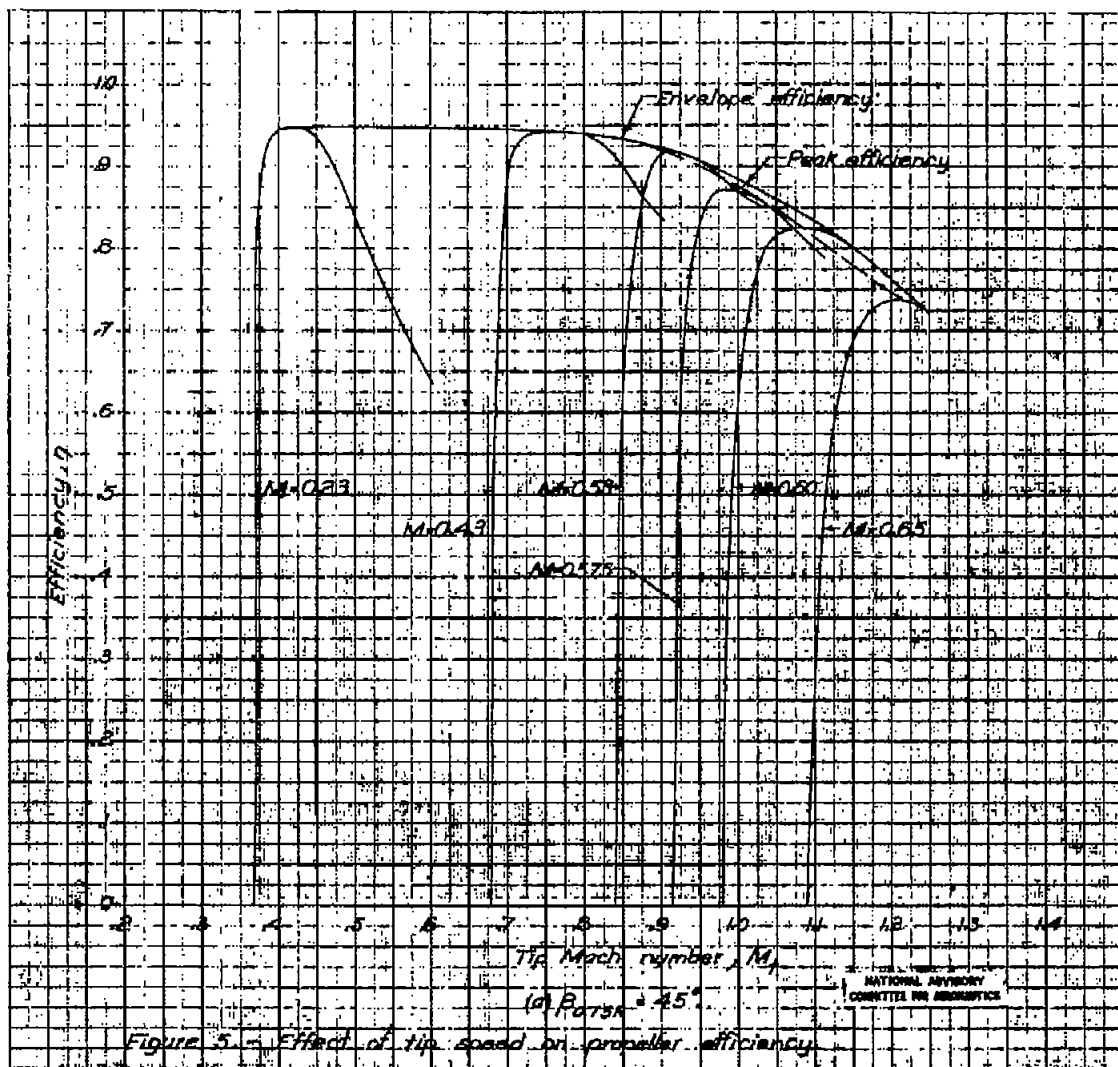


Figure 5 - Effect of tip speed on propeller efficiency

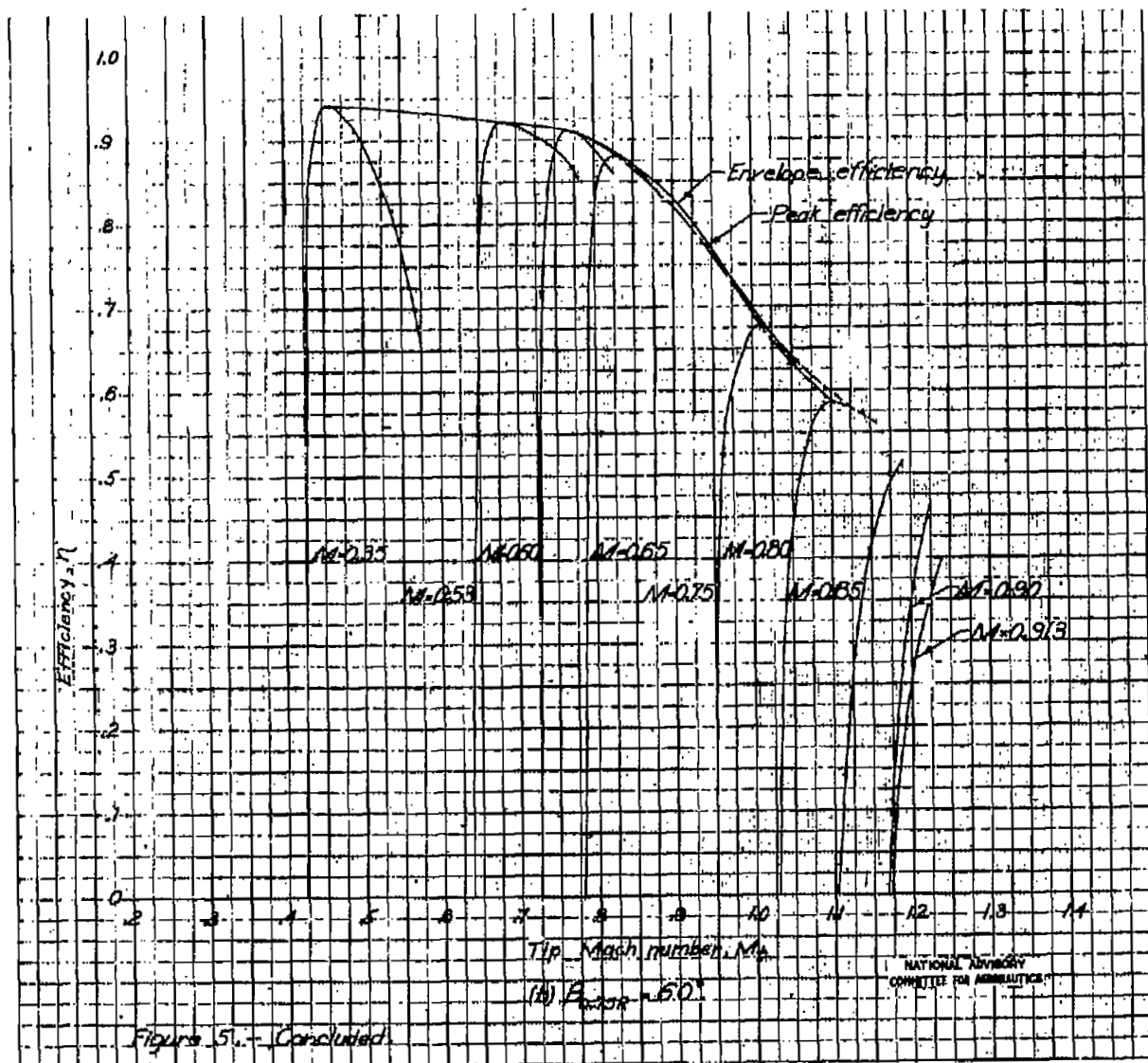
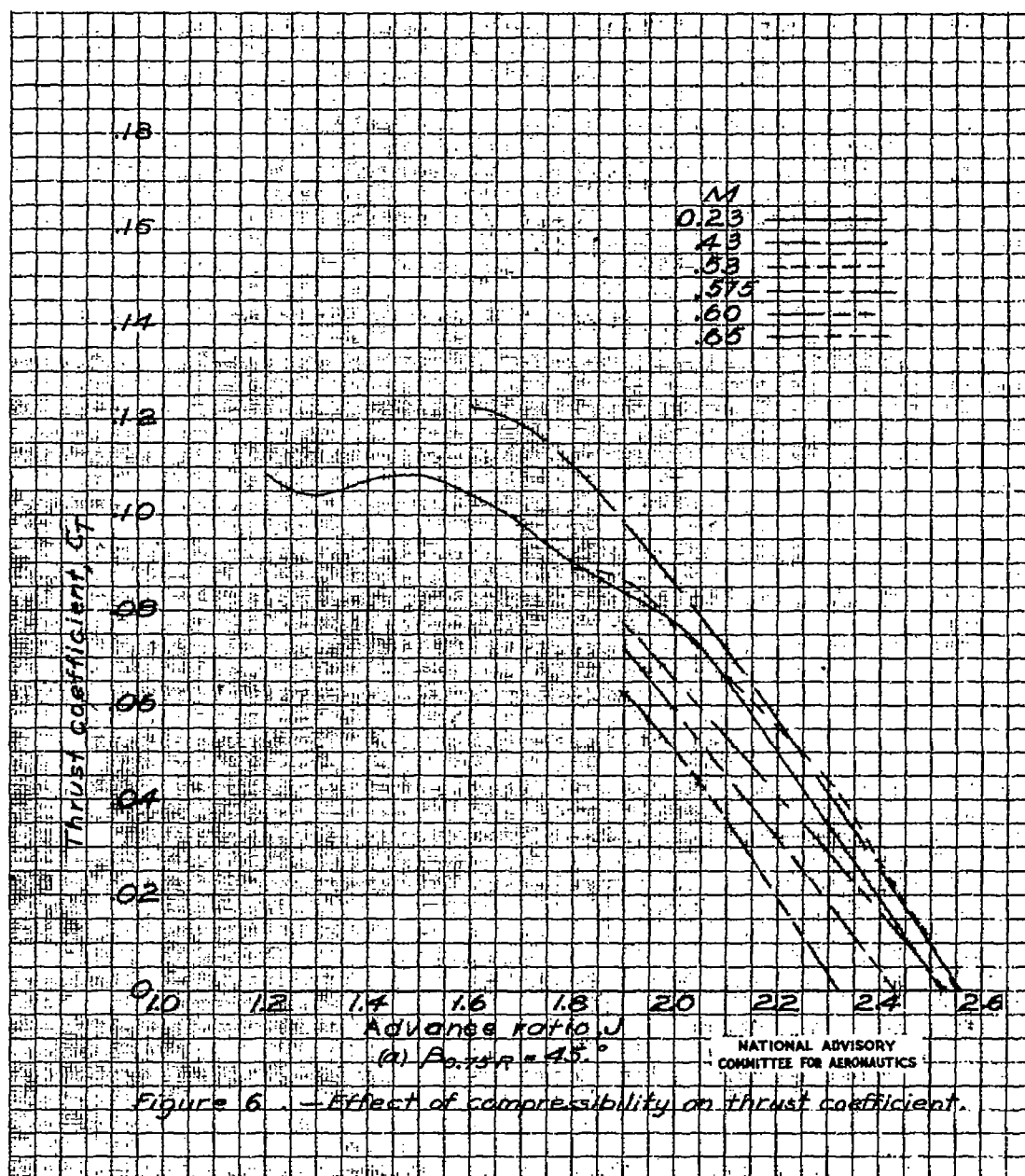


Fig. 5b



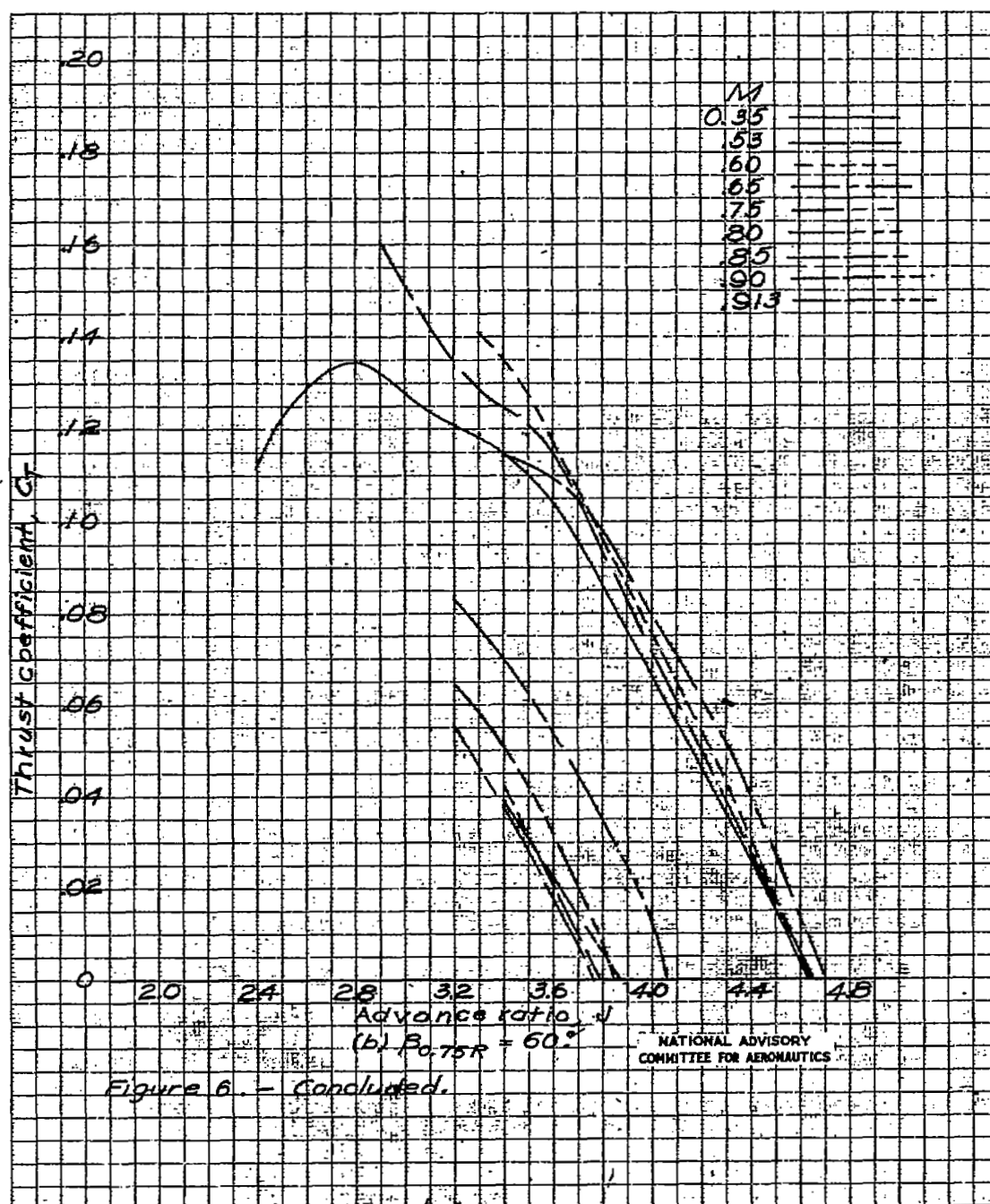
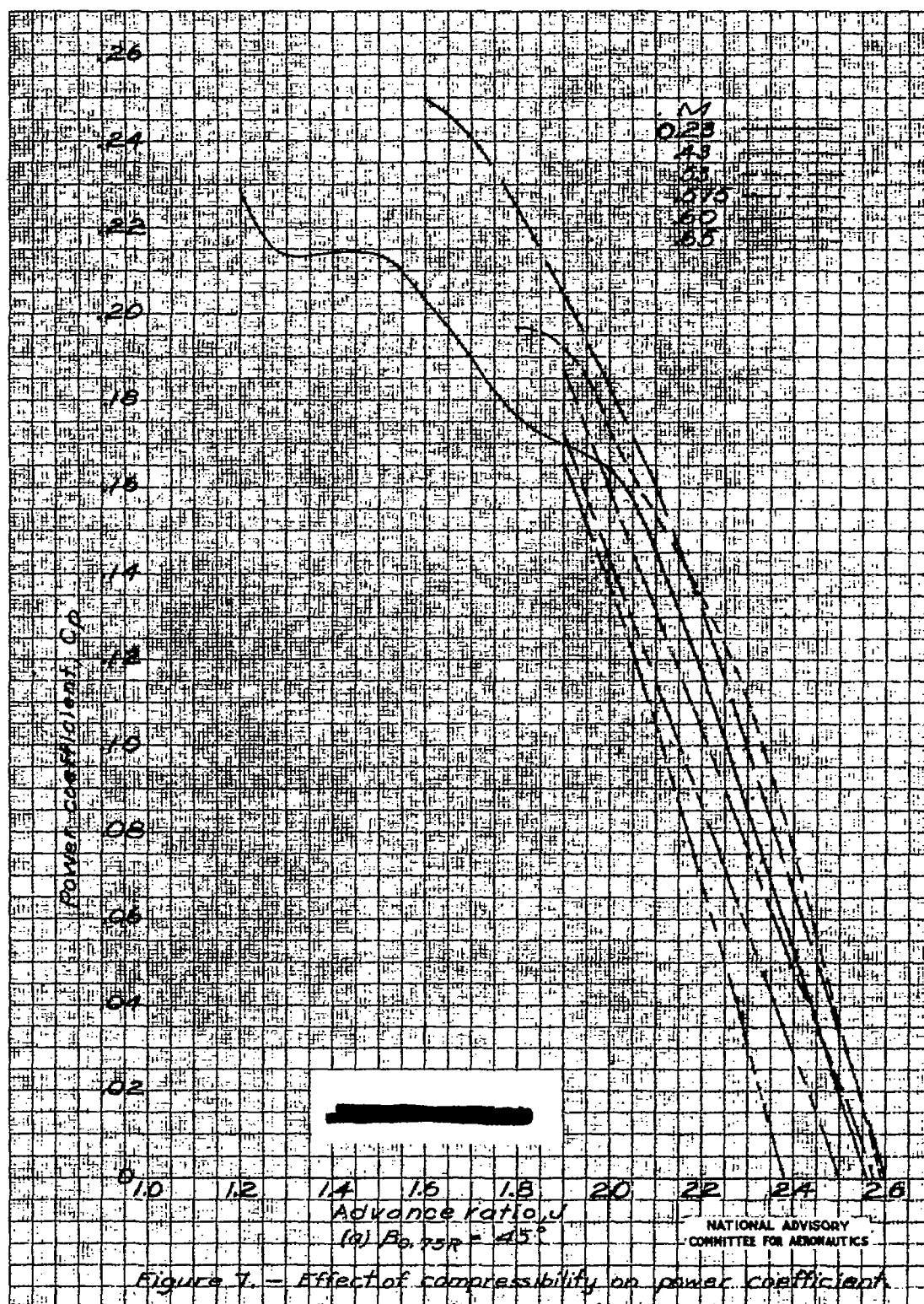
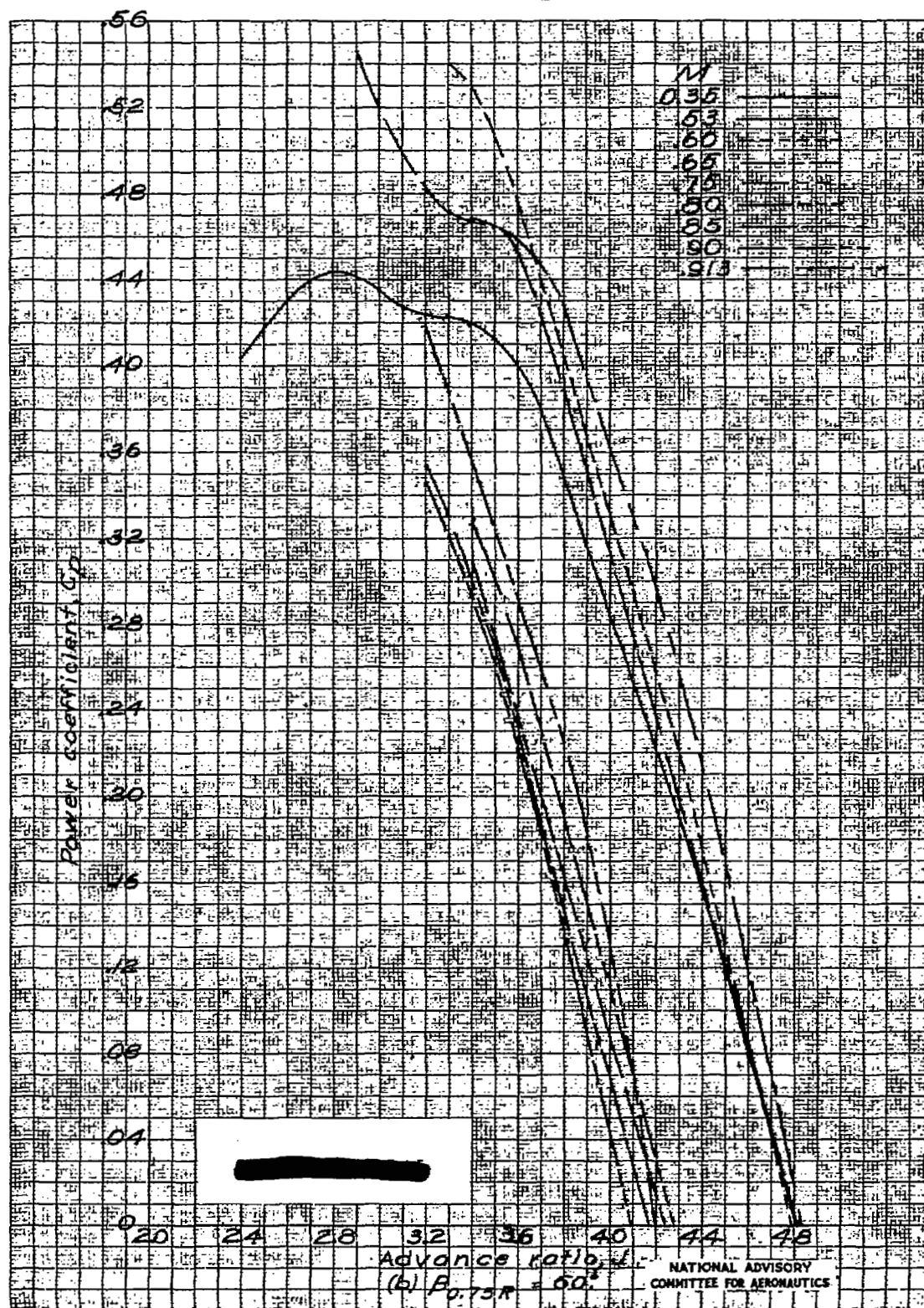
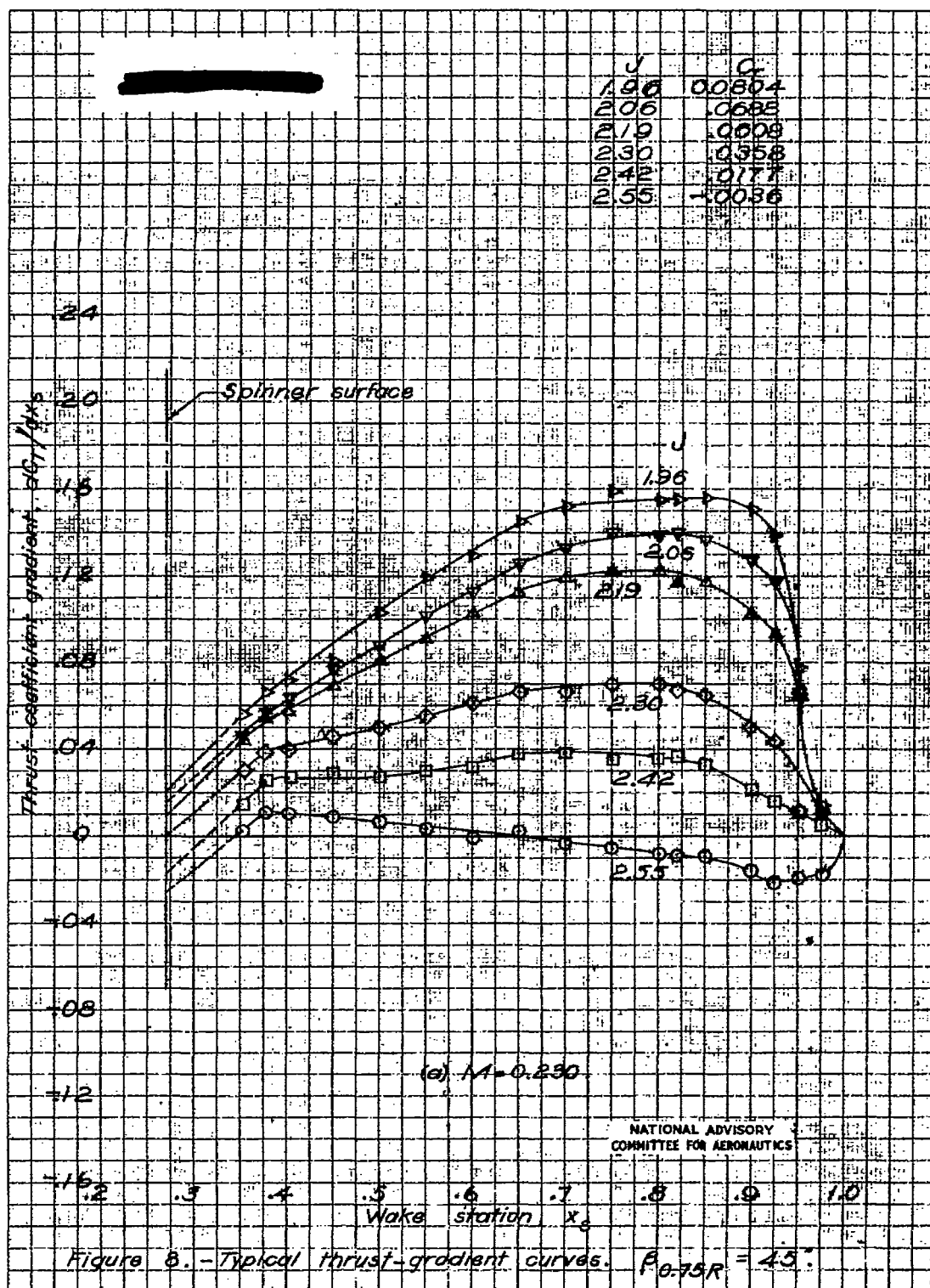


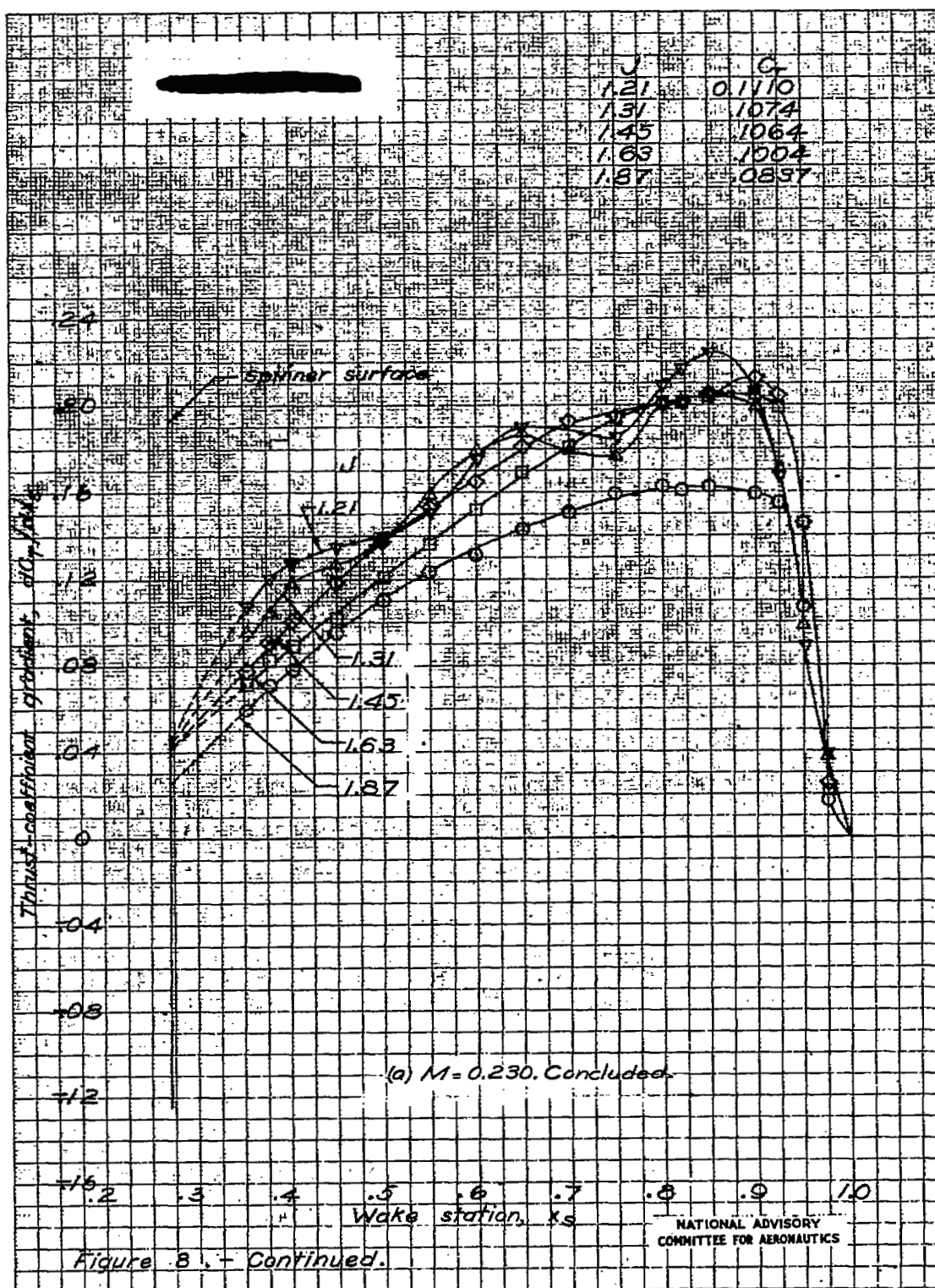
Fig. 7a

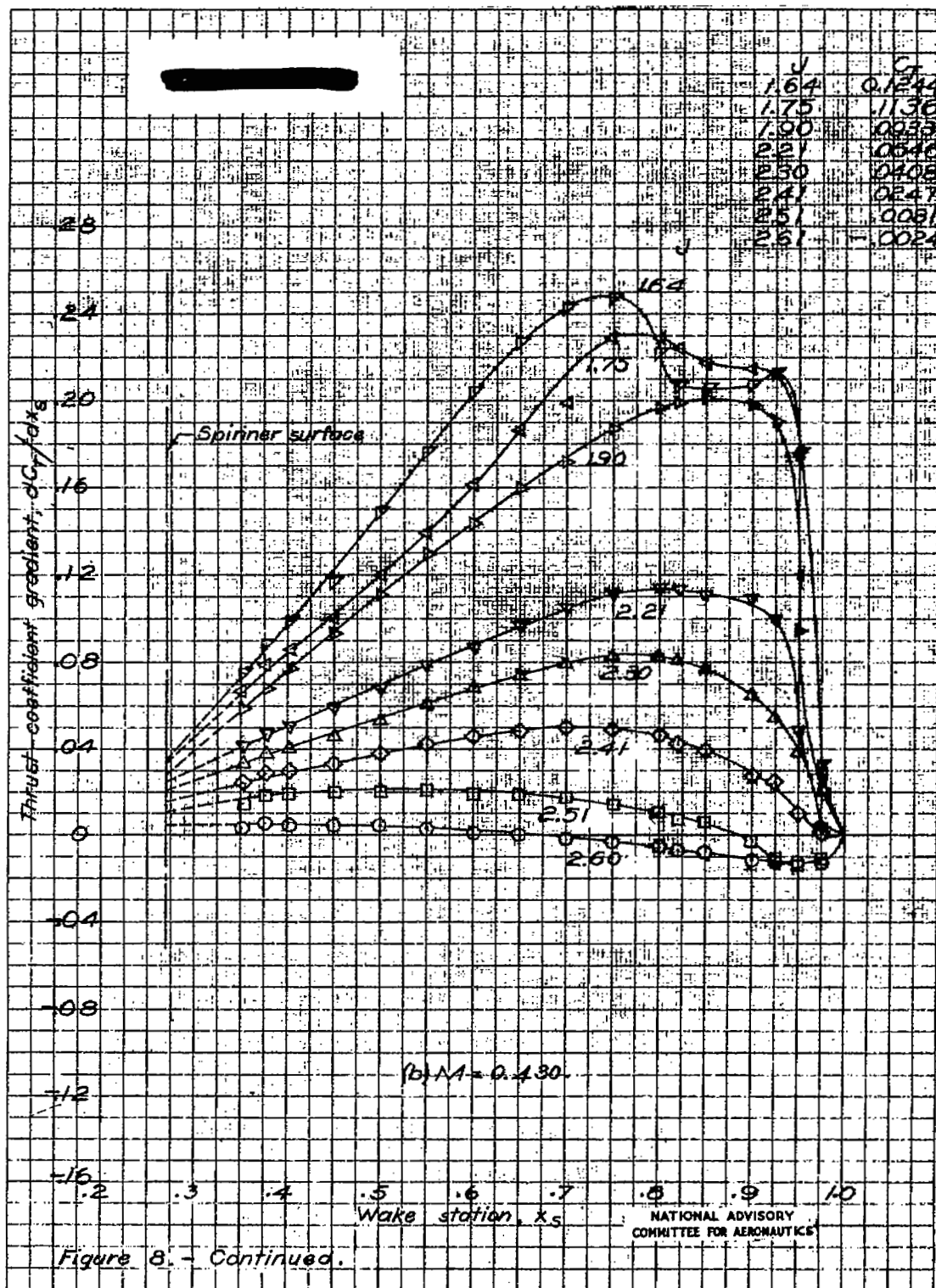
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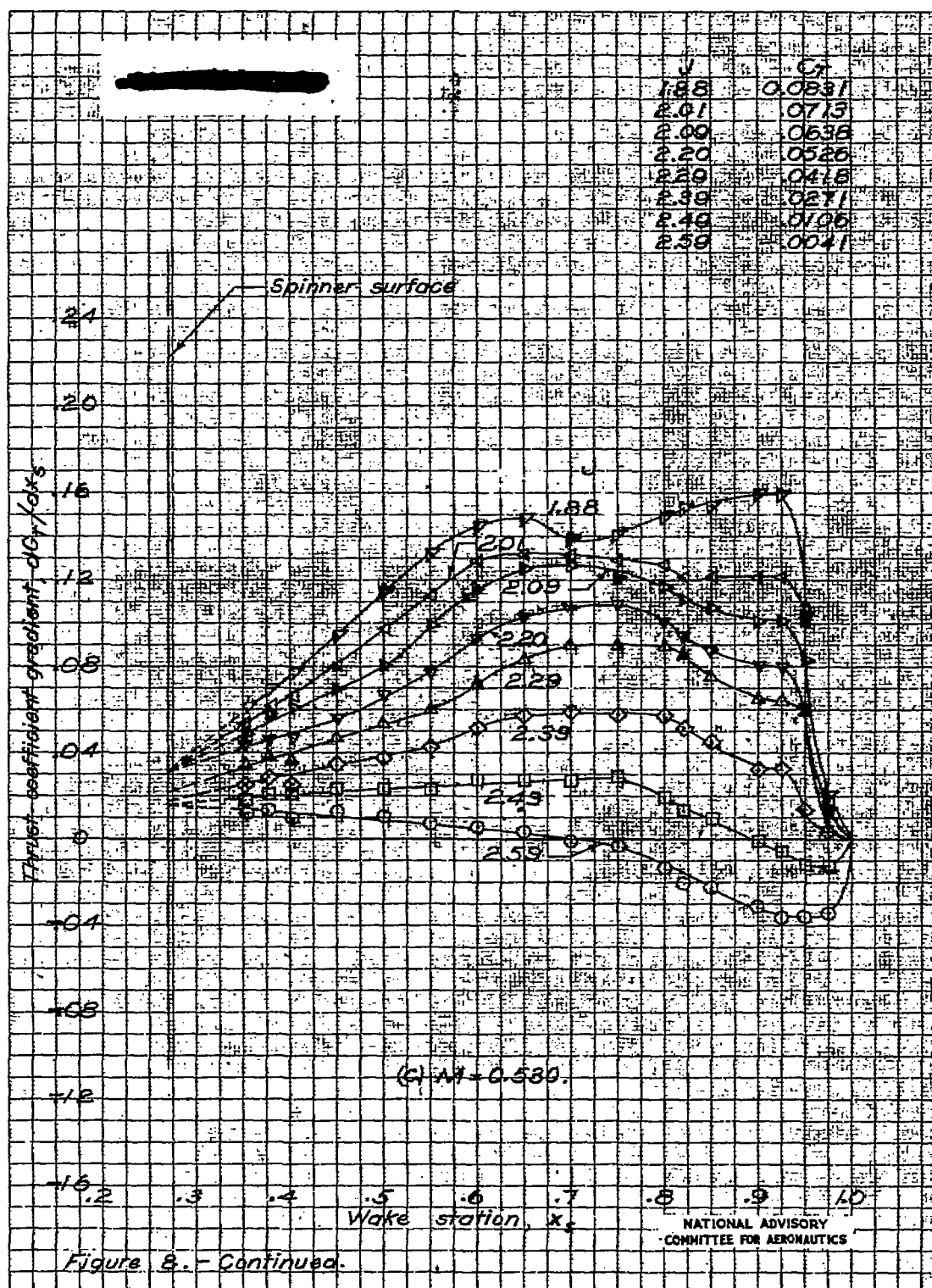
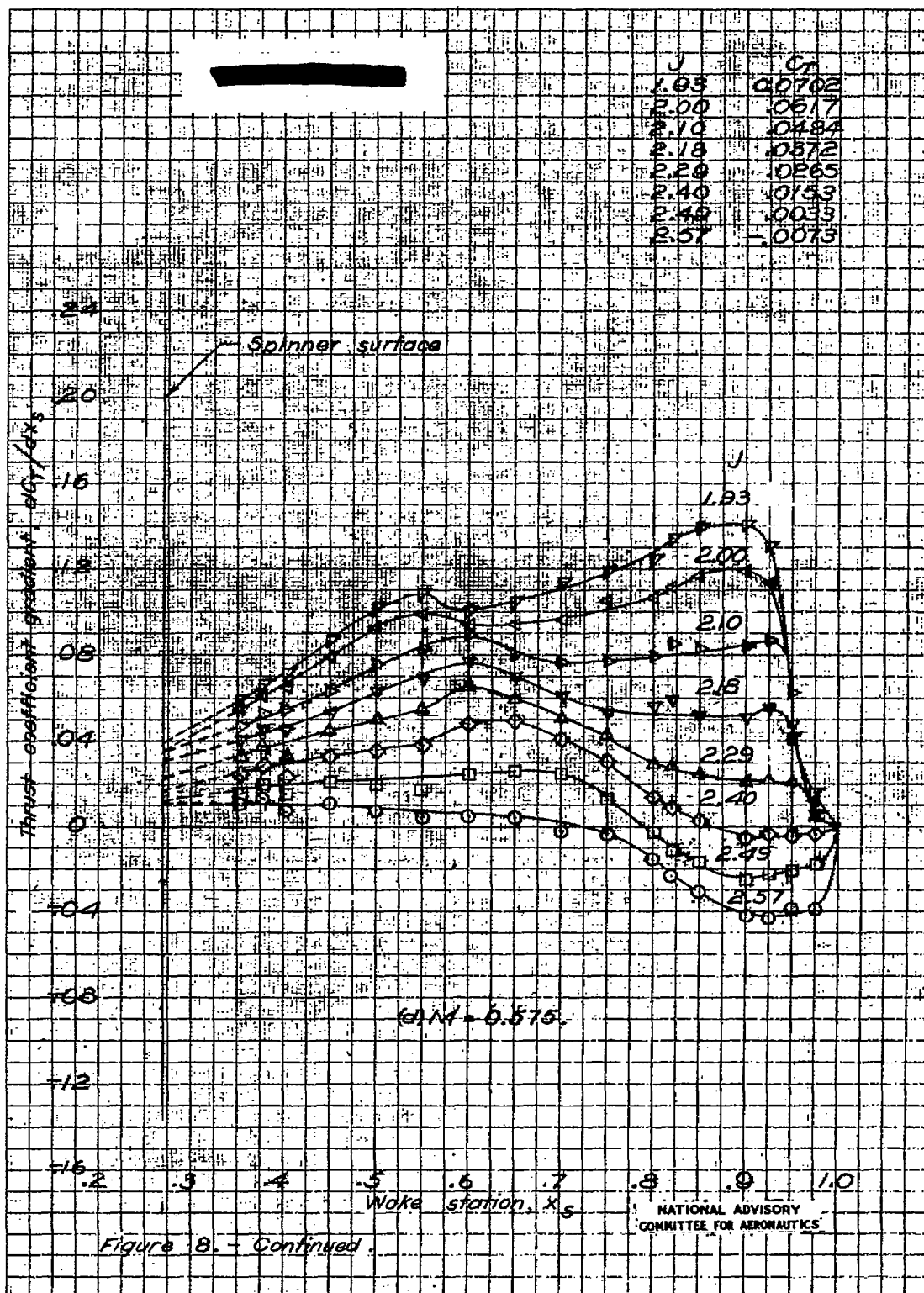
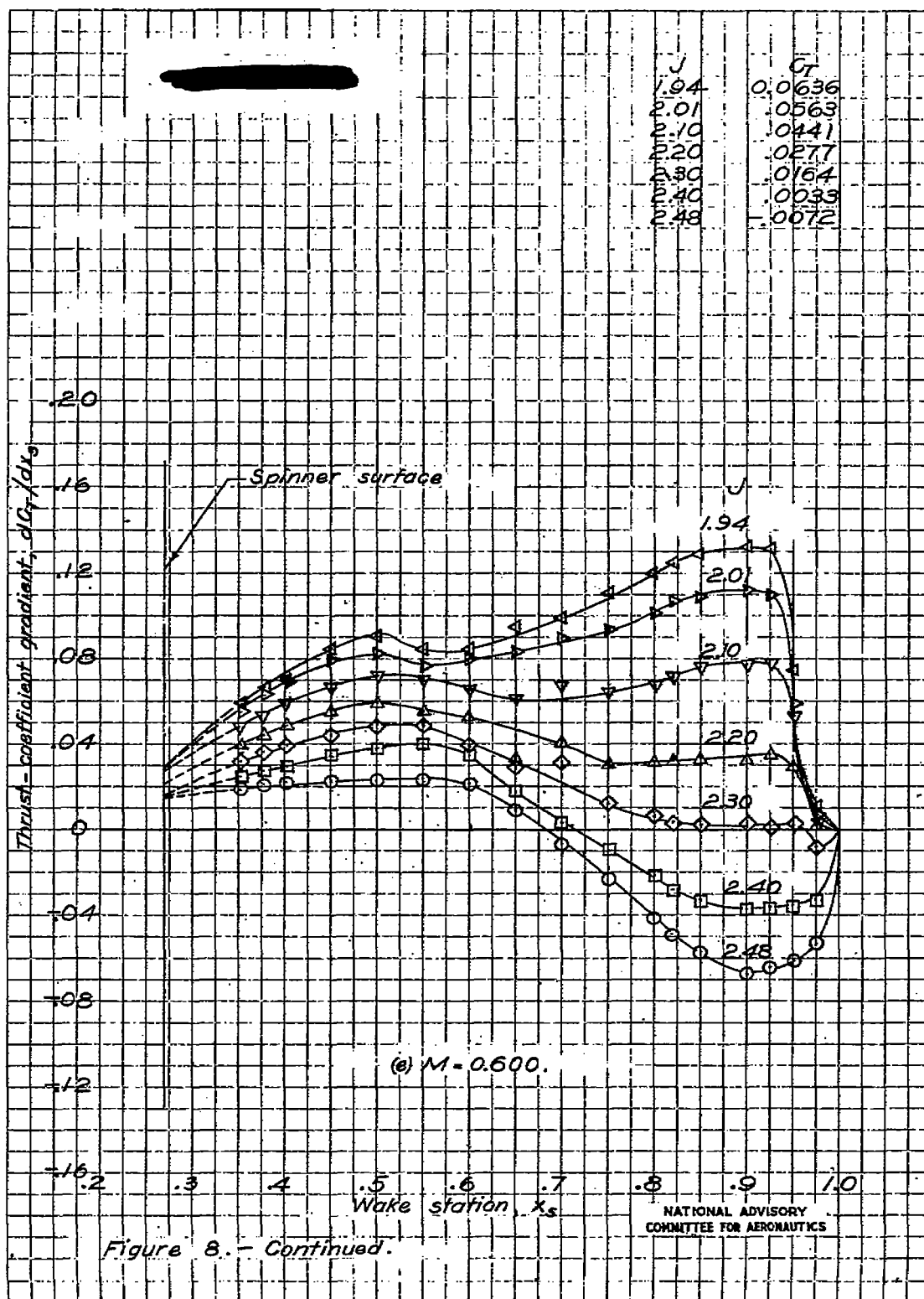


Figure 8. - Continued.





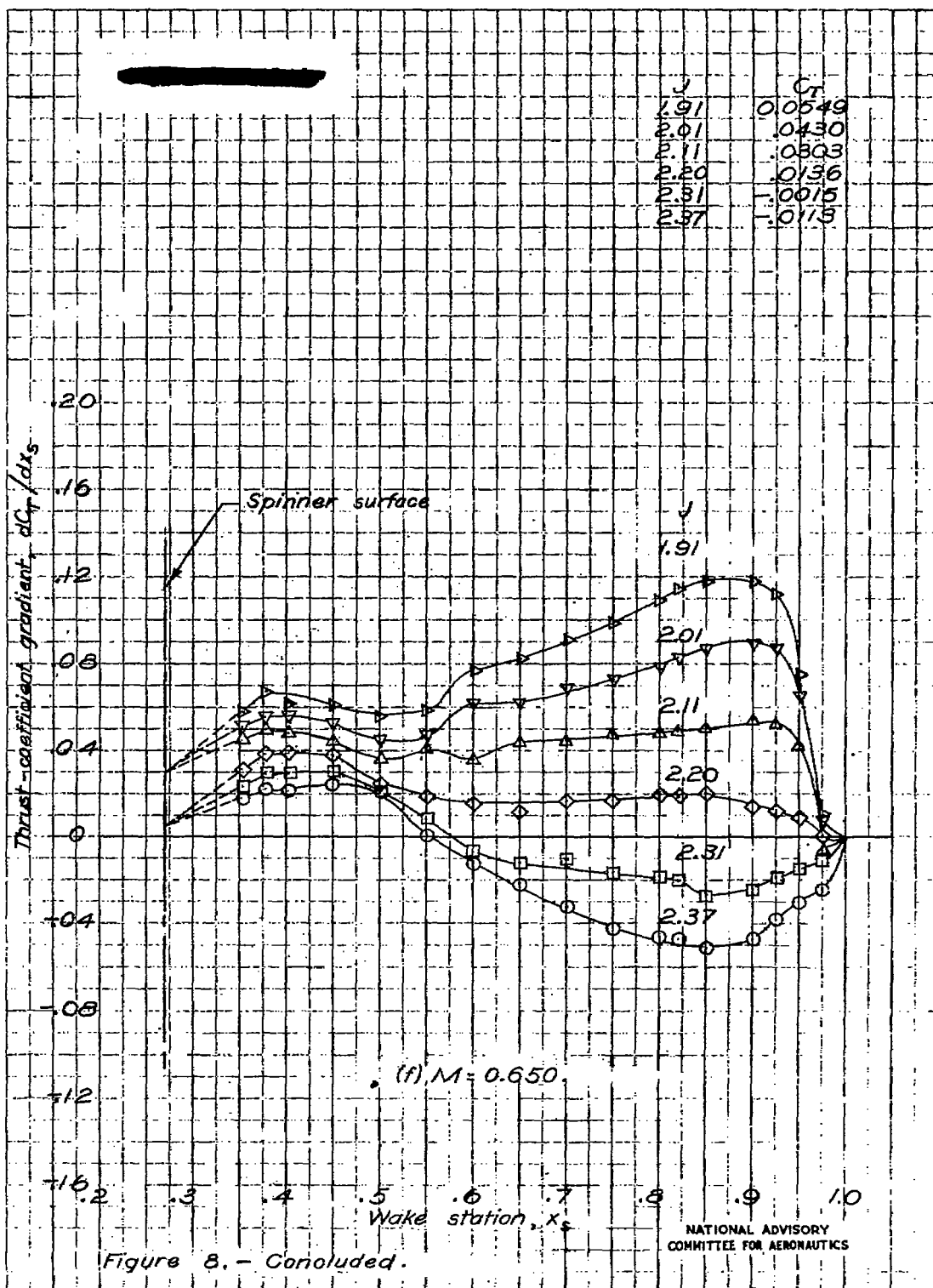


Figure 8. - Concluded.

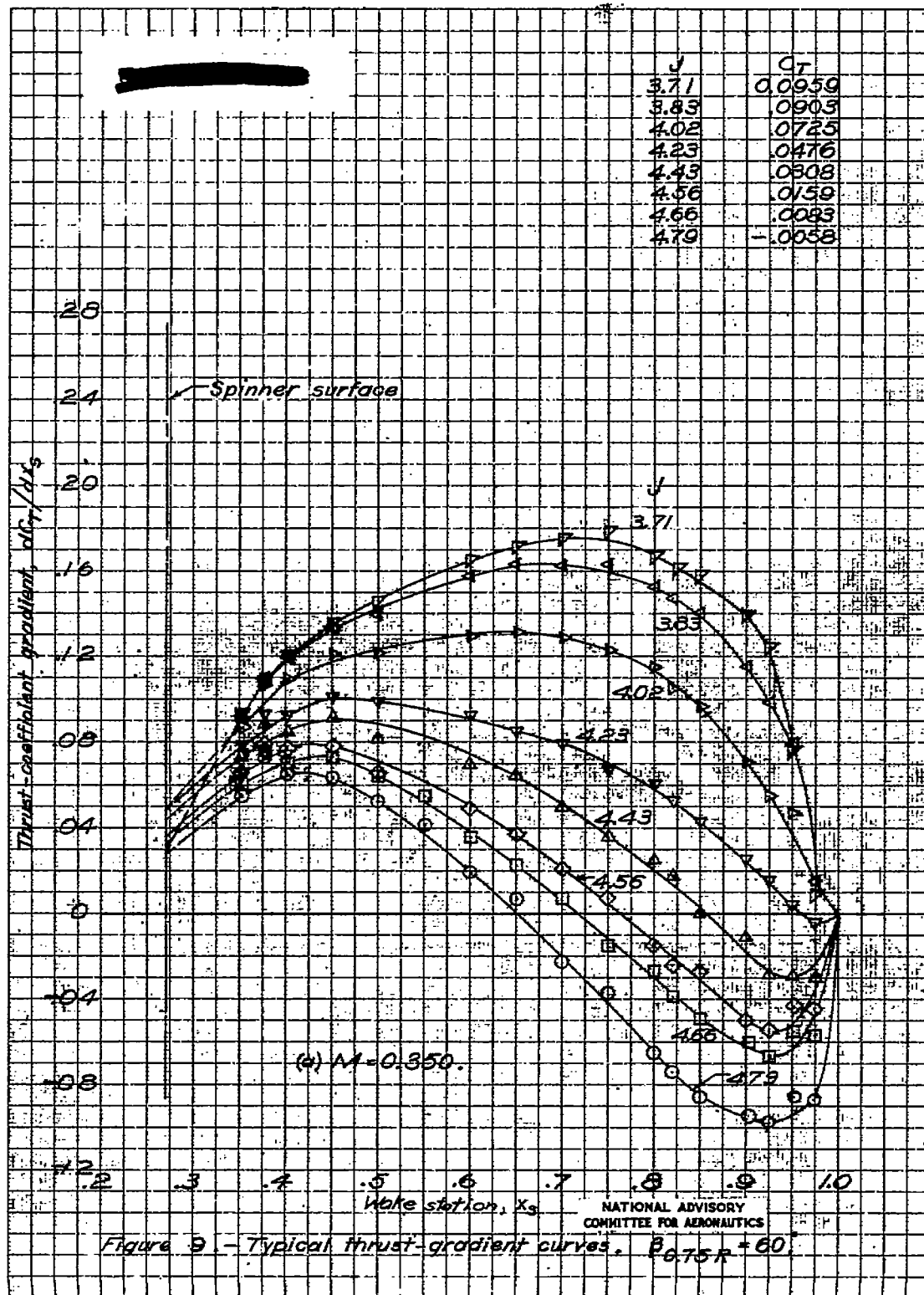
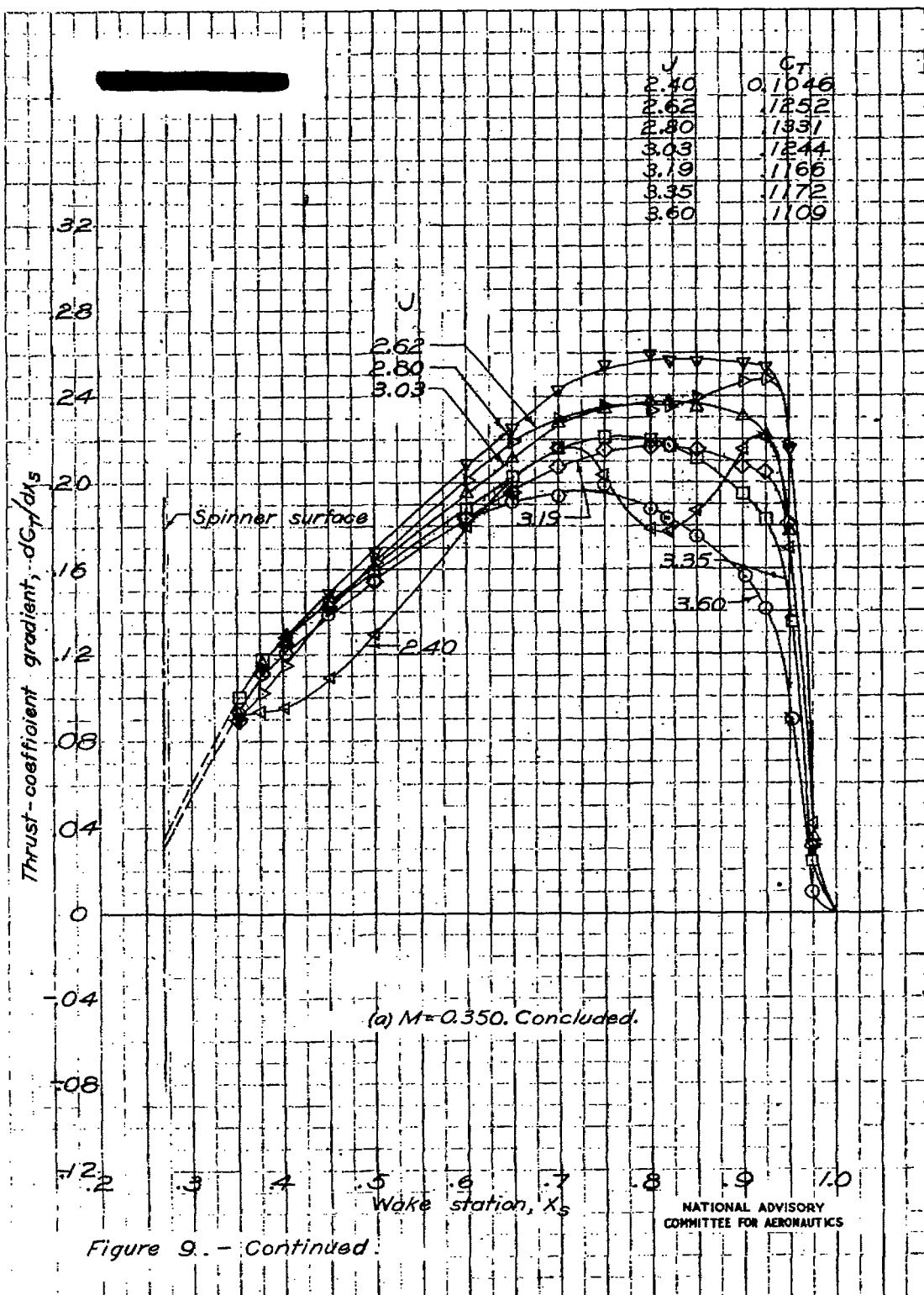
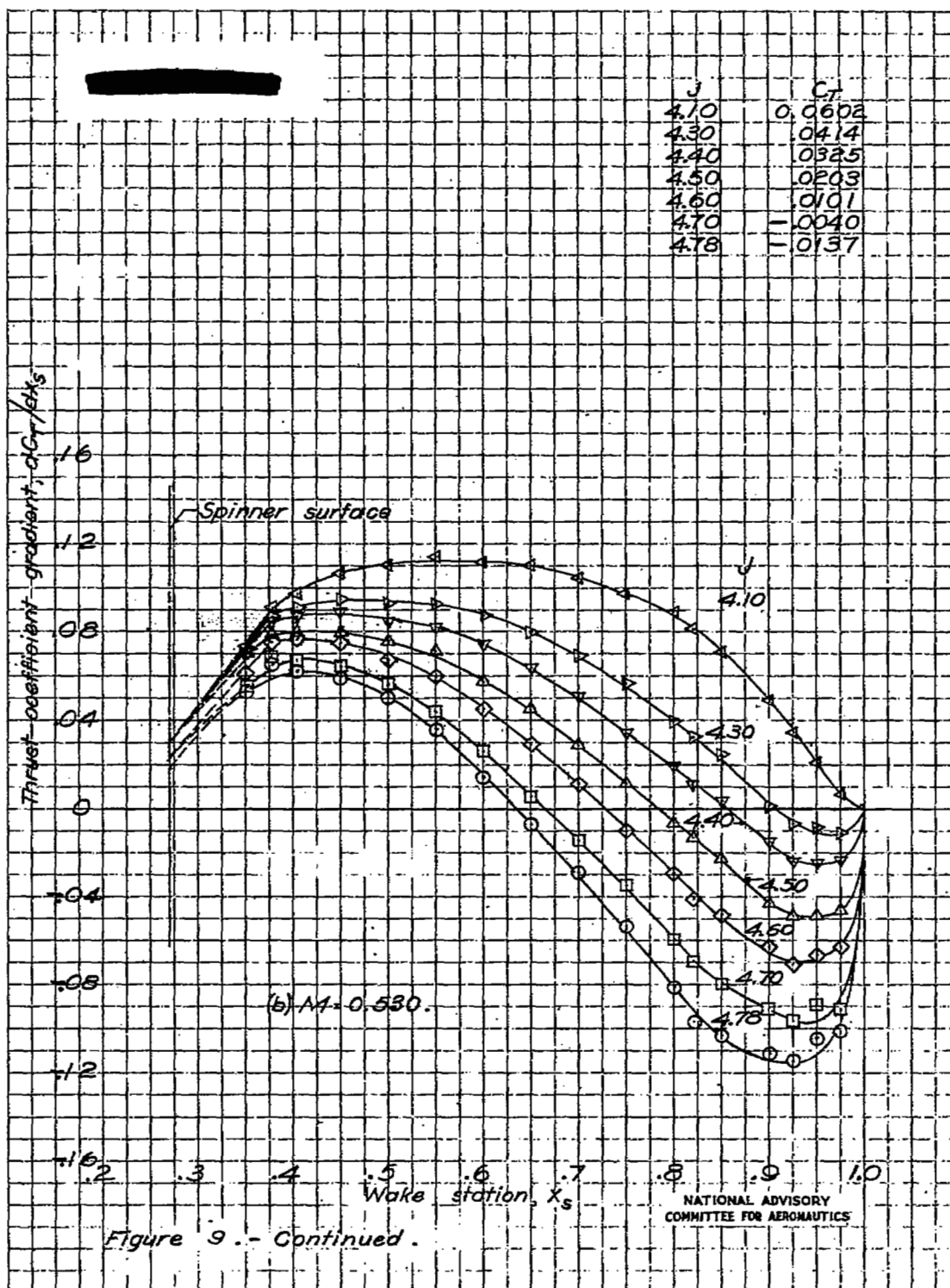


Fig. 9a conc.

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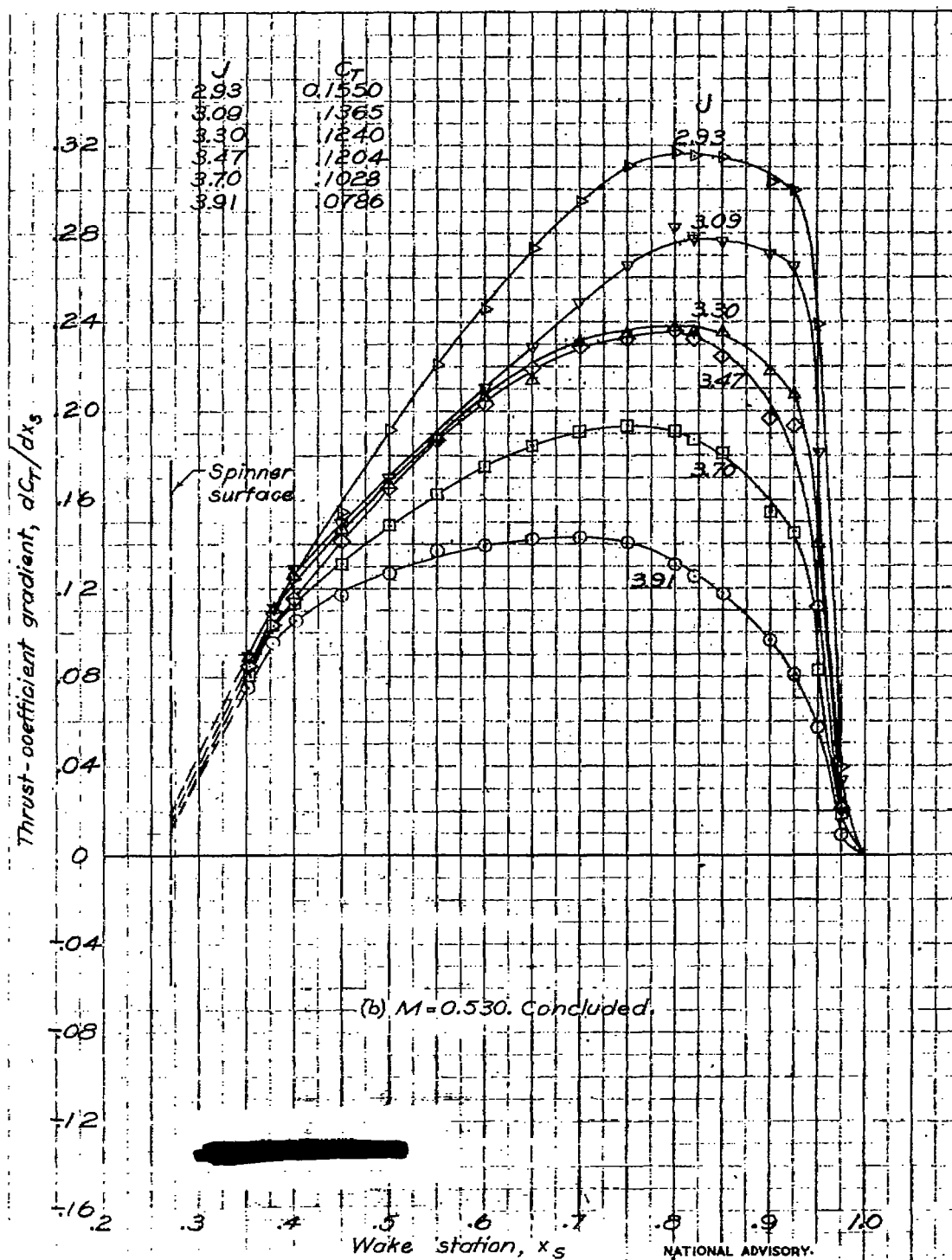


Figure 9.- Continued.

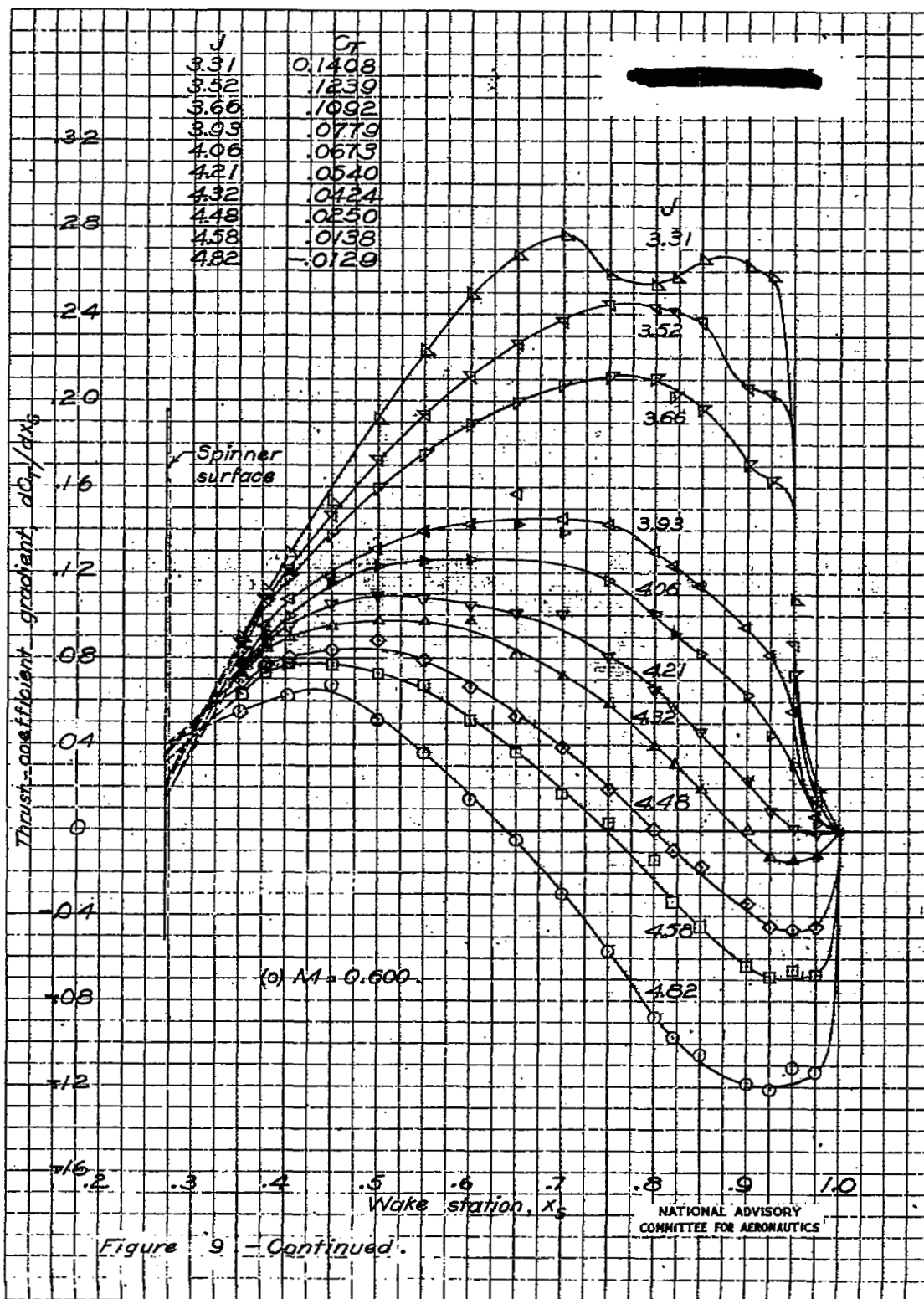


Figure 9 - Continued.

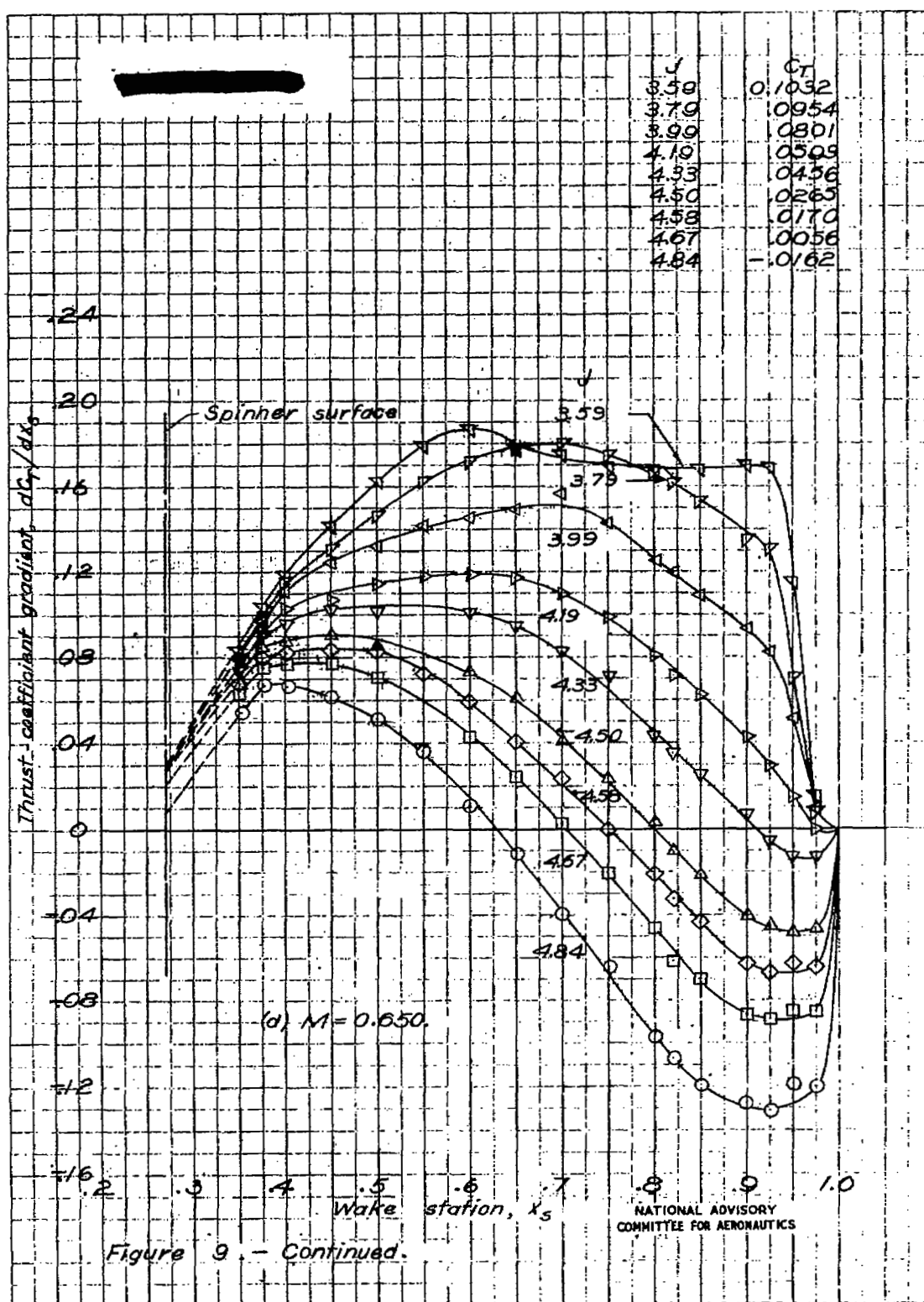


Figure 9 - Continued.

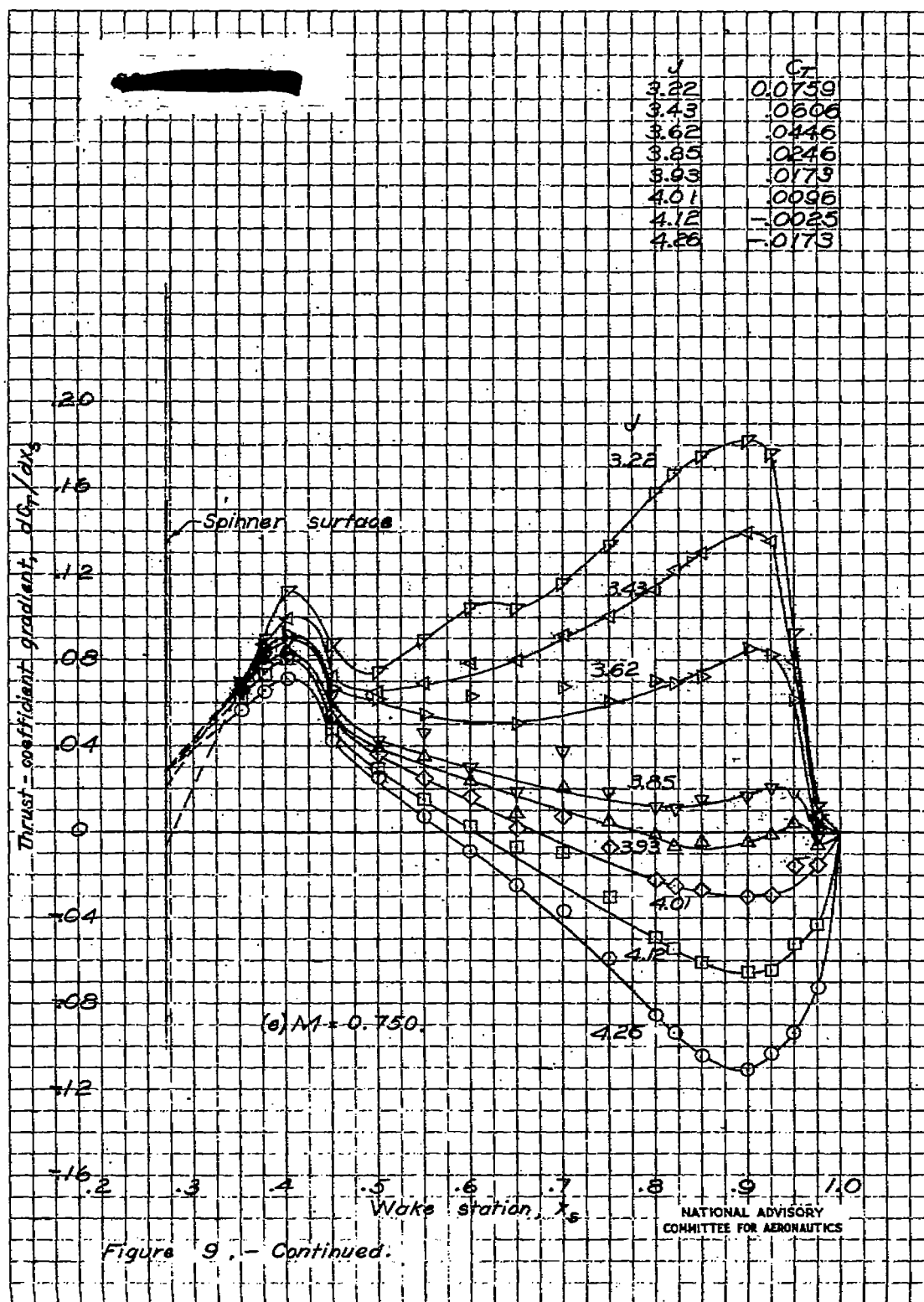
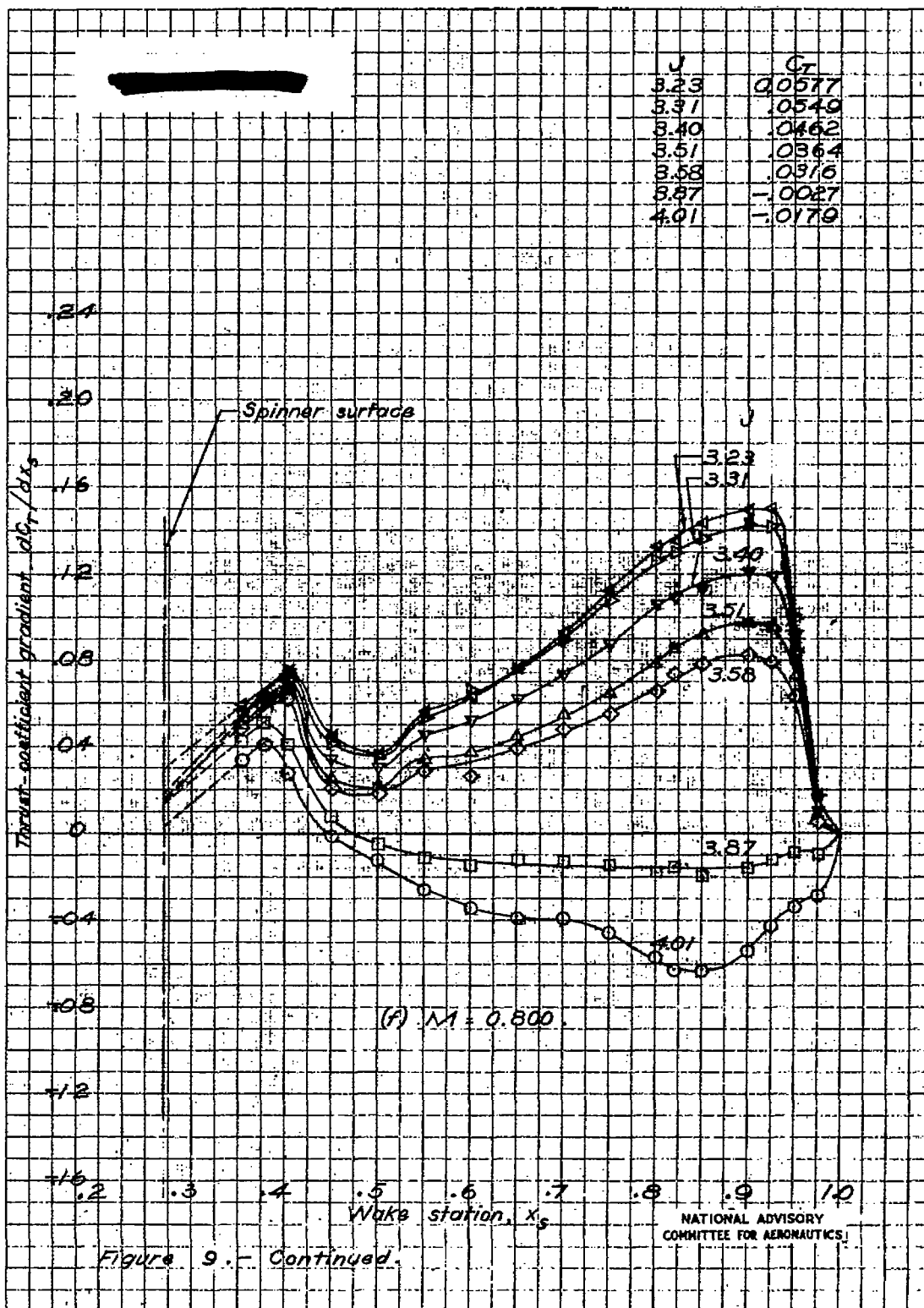
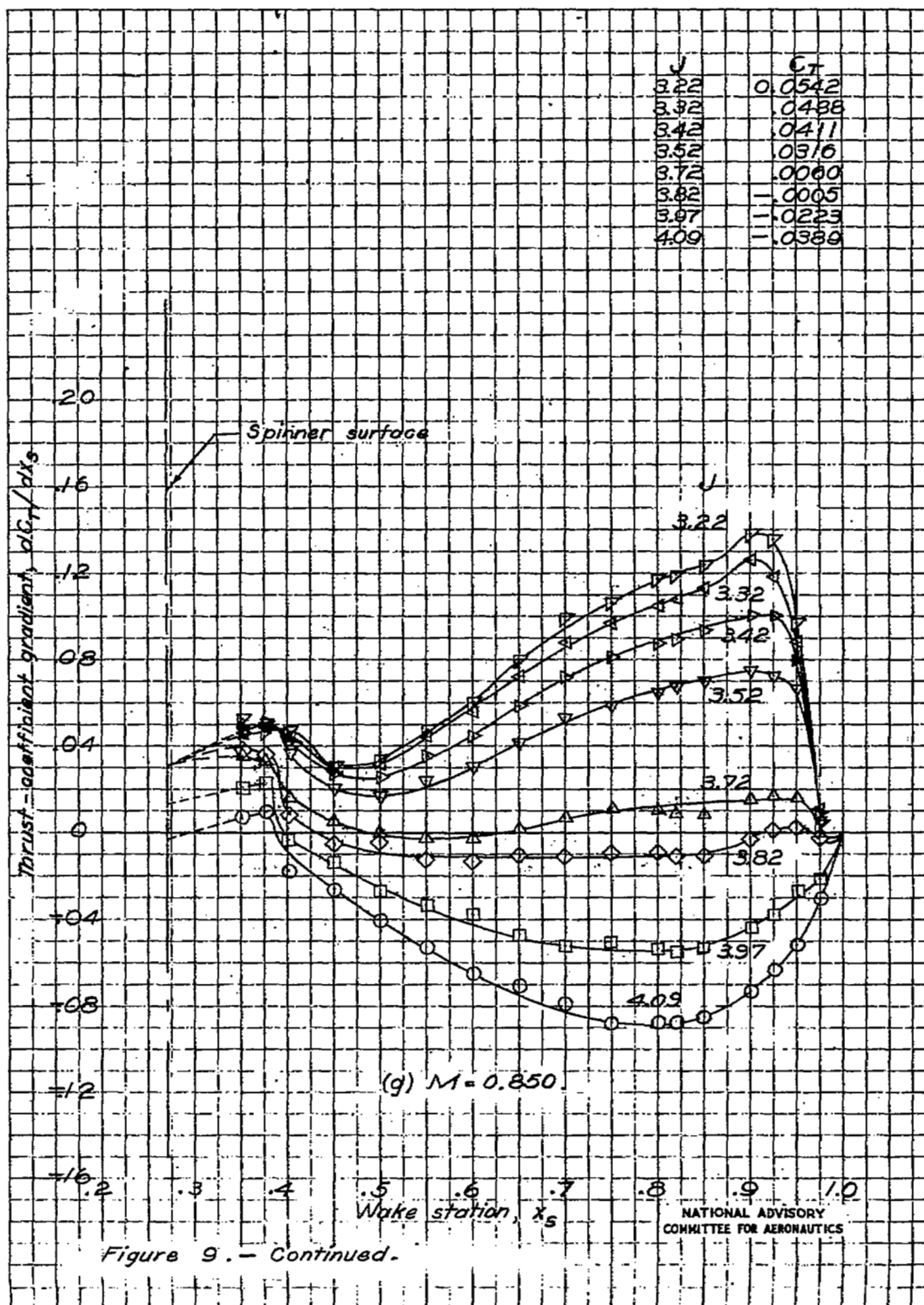
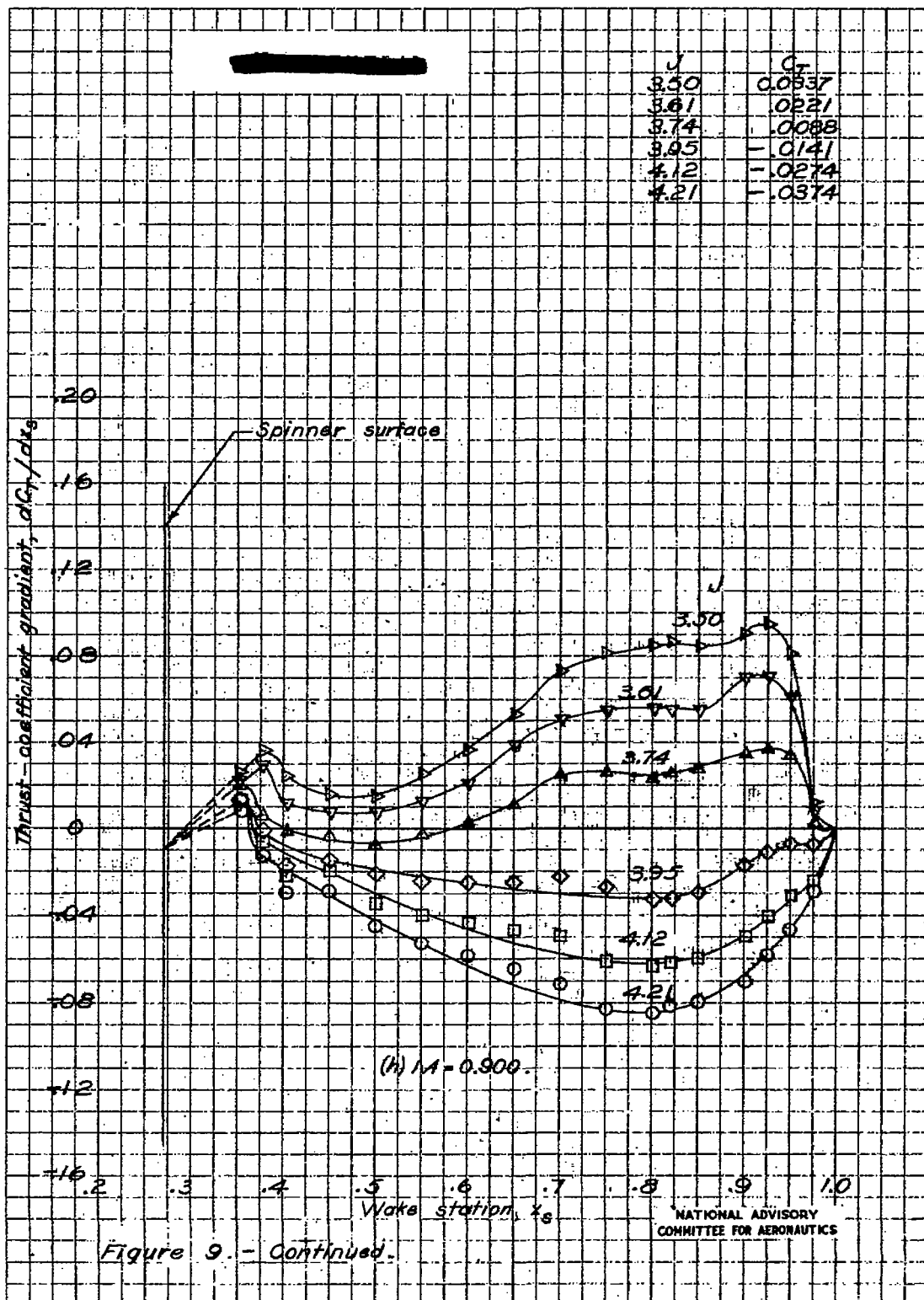
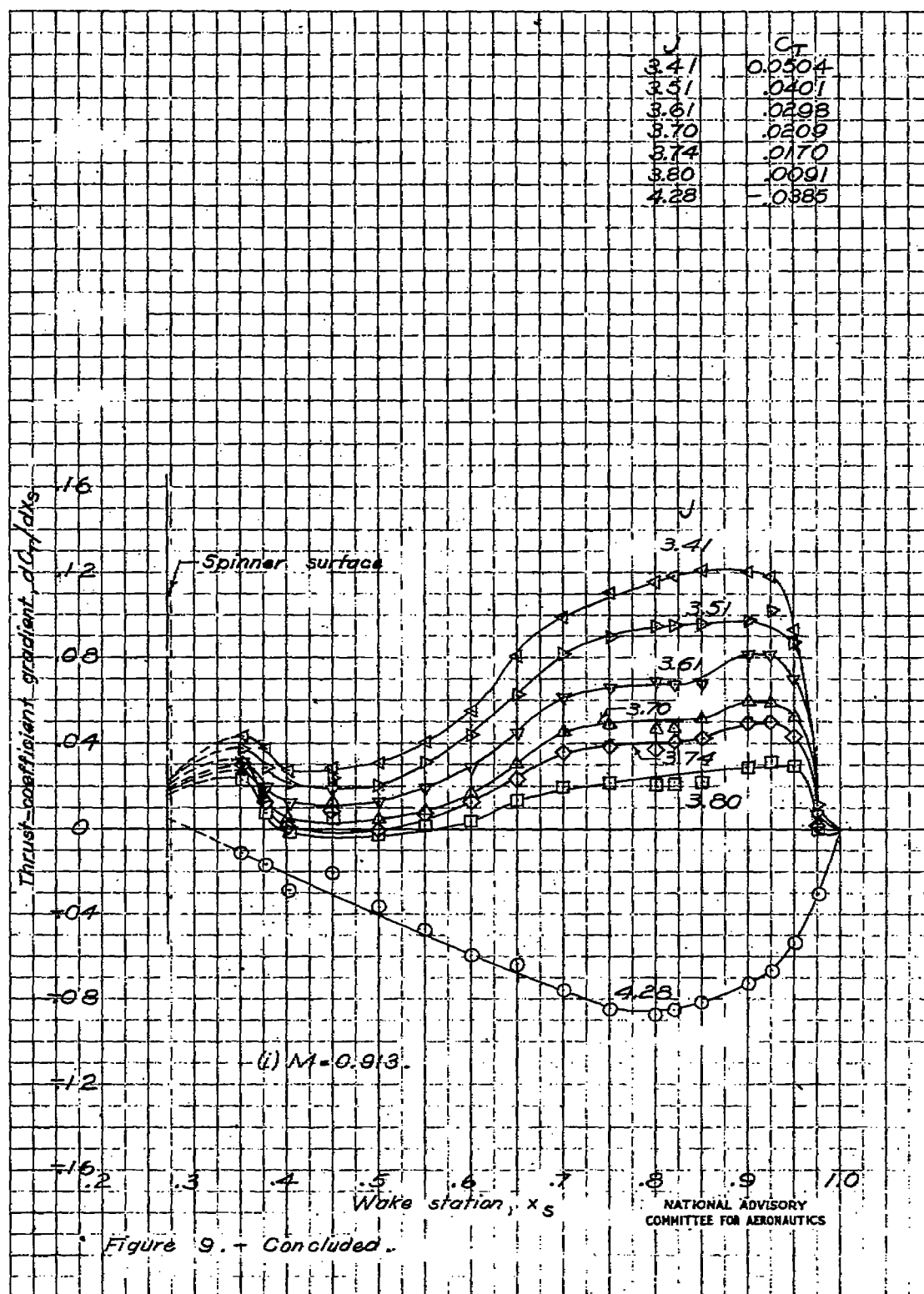


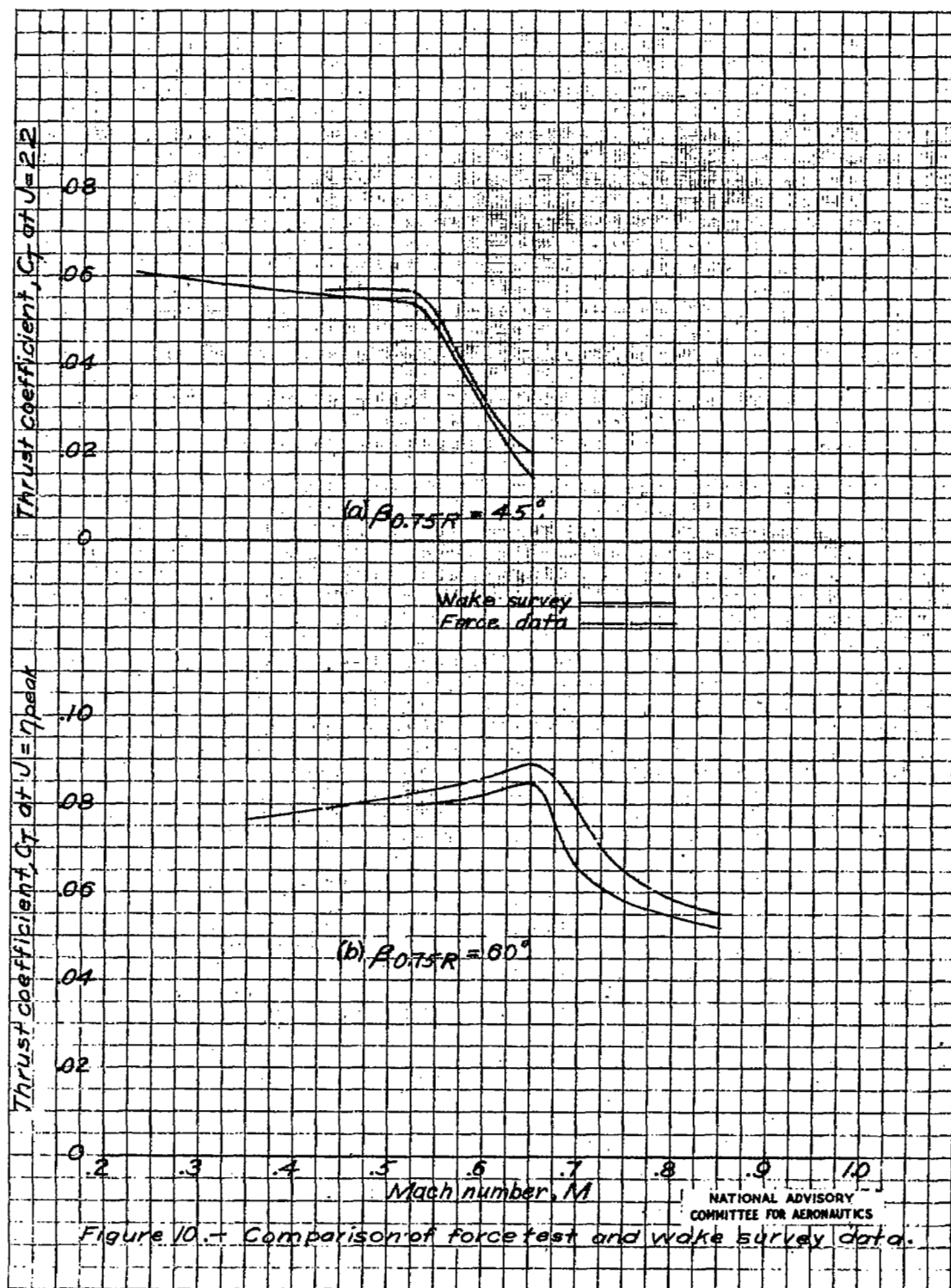
Figure 9. - Continued.

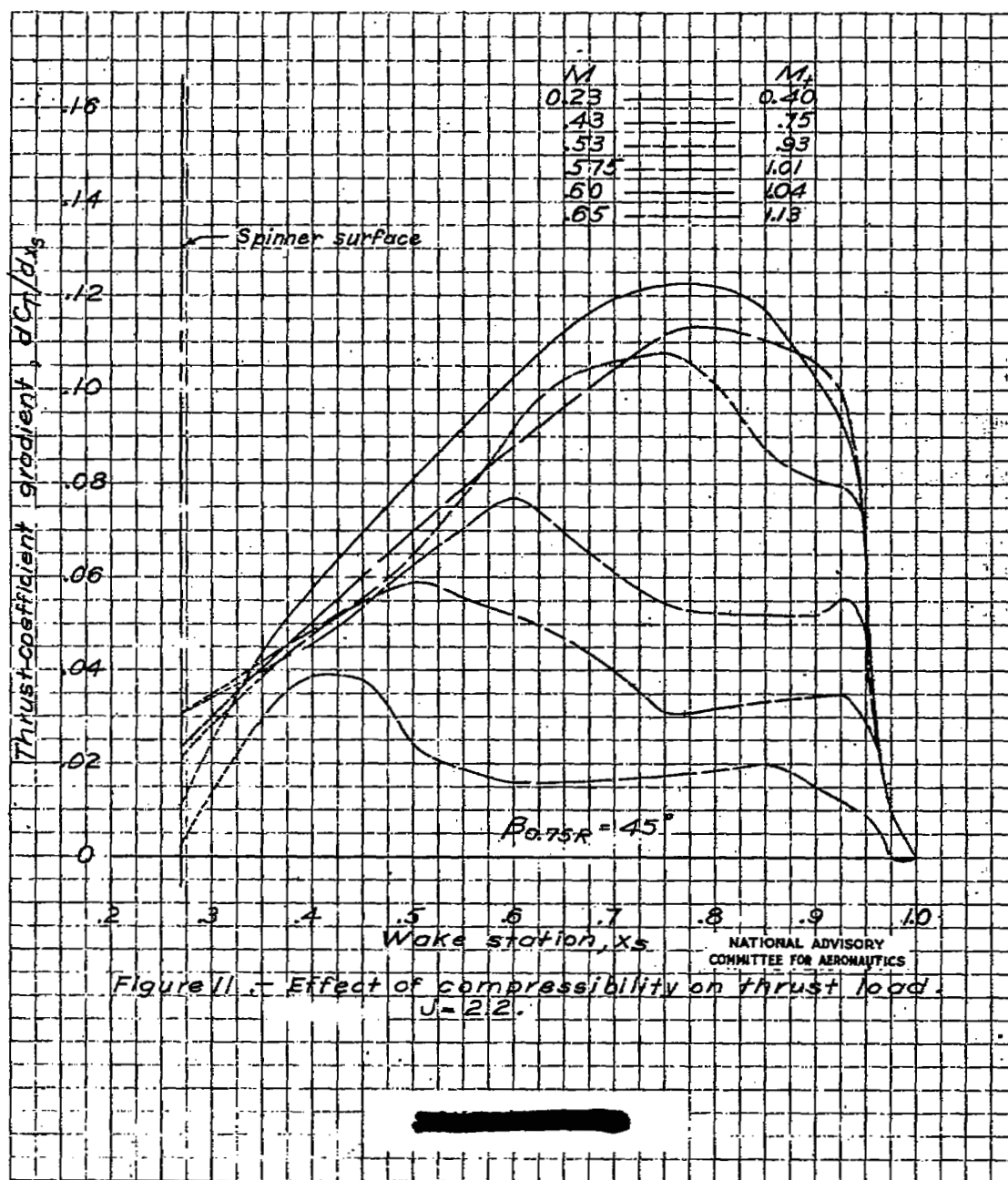


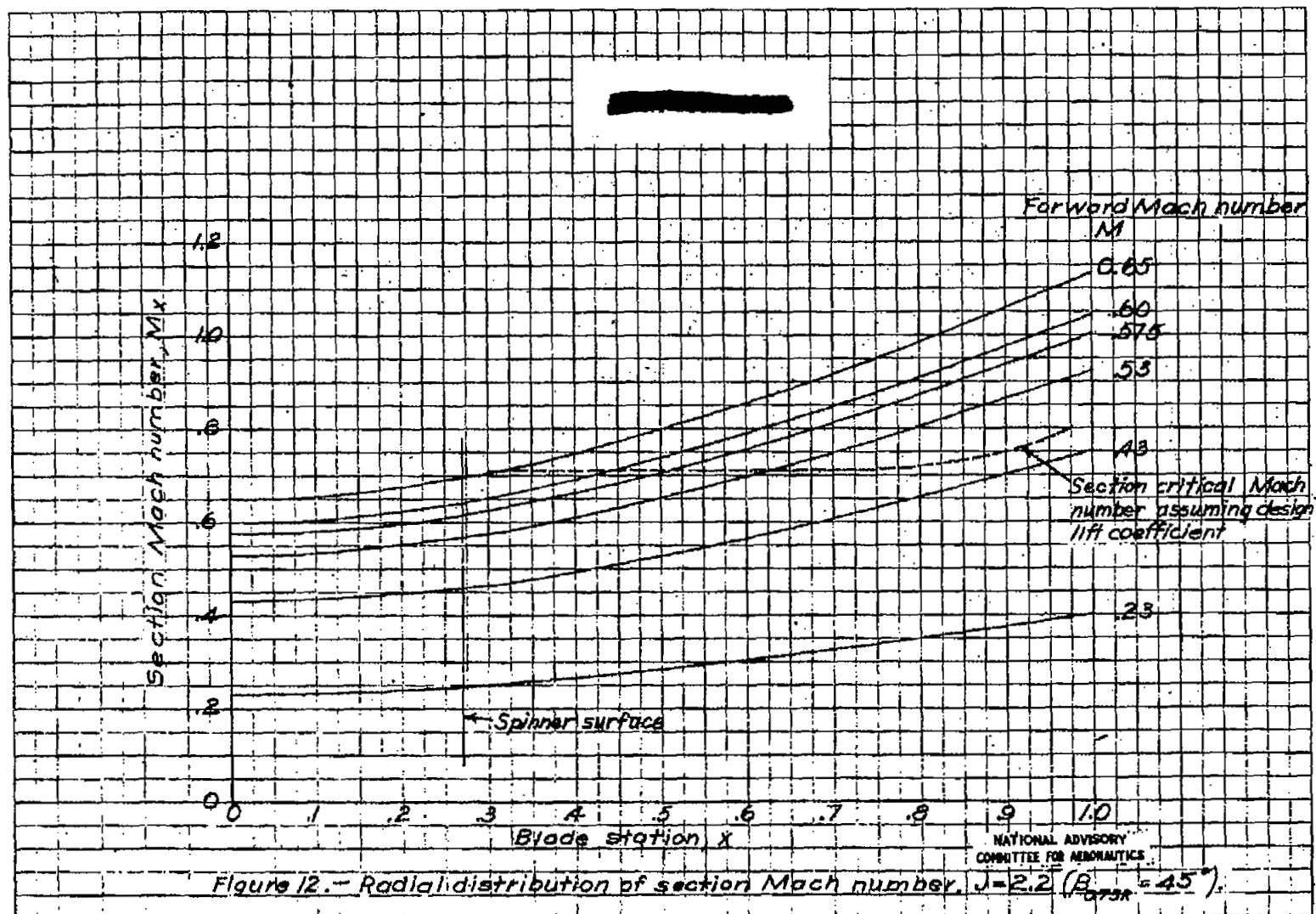












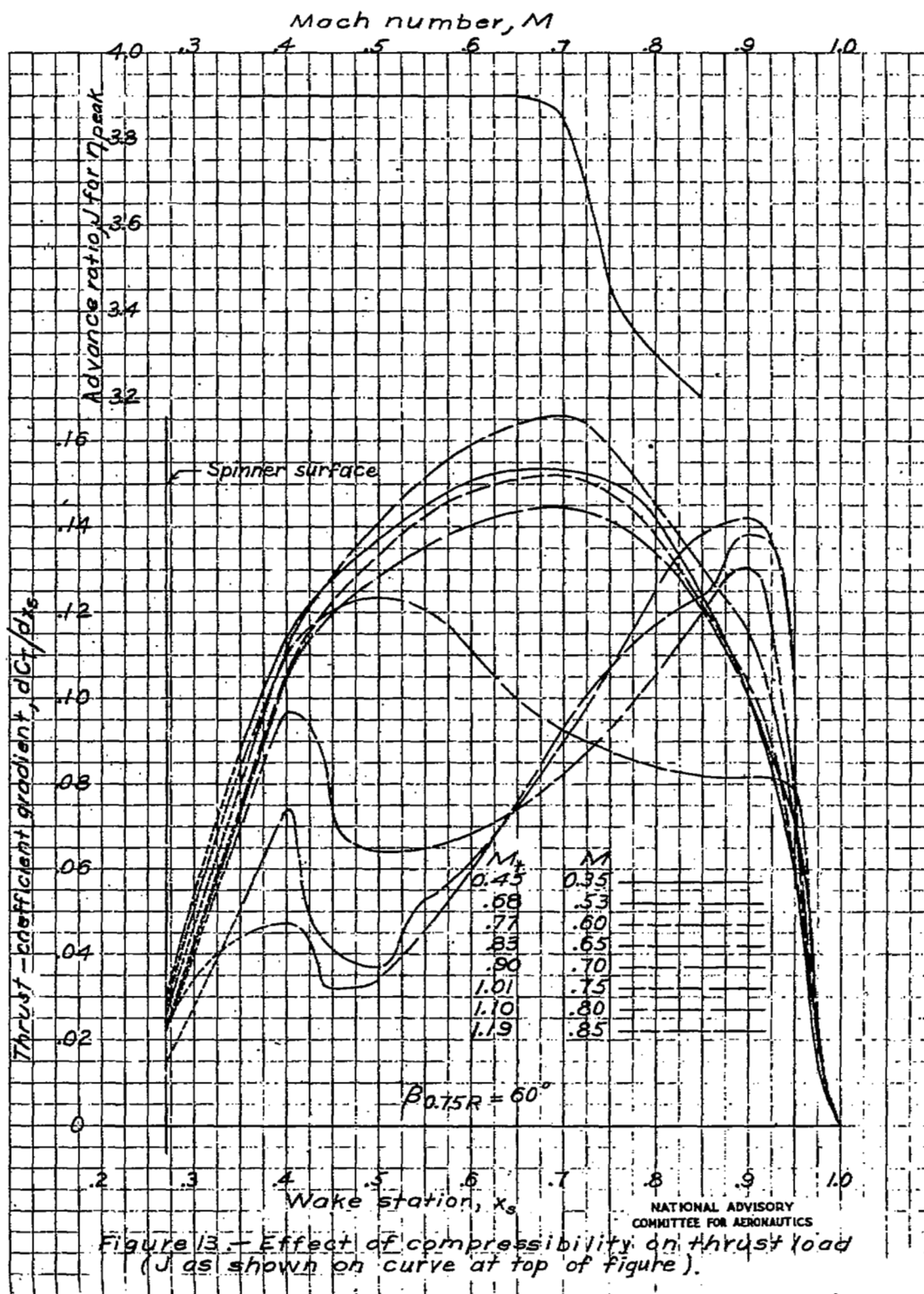


Fig. 14

